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RIP CURRENTS: A PROCESS OF GEOLOGICAL IMPORTANCE[1]

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ABSTRACT

Rip currents are defined as seaward-moving streaks of water which return the water carried landward by waves. These currents are believed to be an almost universal accompaniment of large waves breaking on an exposed coast.

Unlike the largely hypothetical undertow, rip currents flow principally at and near the surface. They attain velocities up to at least 2 miles an hour and extend on occasions for 1,000 feet or more from the shore. Geologically the currents are of importance, since they carry a suspended load of fine sediment out from the shore. Small channels in the sand are produced by the flow in the near-shore portions of the rip currents. The development and changes of these channels have been investigated. The strong outflow of the current and the presence of the channels along the bottom constitute a serious danger to inexperienced swimmers.

INTRODUCTION

The observation that a stick thrown into the breakers from a beach will usually return to the shore demonstrates that surface water is carried landward in the breaker zone in the absence of an offshore wind. Floating objects seaward of the breaker zone are also observed to move toward land but at a slower rate. Thus objects thrown into the sea at the end of the 1,000-foot Scripps pier (Fig. 1) almost invariably move shoreward, although their move-

[1] Contribution from the Scripps Institution of Oceanography. New Series No. 126. Assistance in the preparation of these materials was furnished by the personnel of the Works Progress Administration, Official Projects No. 665-07-3-141 and No. 65-1-07-2317.

ment usually has a longshore component. A return flow required by this landward movement has led to the idea that the water returns beneath the surface. The popular idea of violent undertow which is said to pull bathers beneath the surface was first challenged by W. M. Davis,[2] and a considerable discussion of the subject ensued. Conflicting evidence was presented, centered chiefly on whether bathers were dragged out from the beaches or whether the waves had as much forward as backward transport.[3]

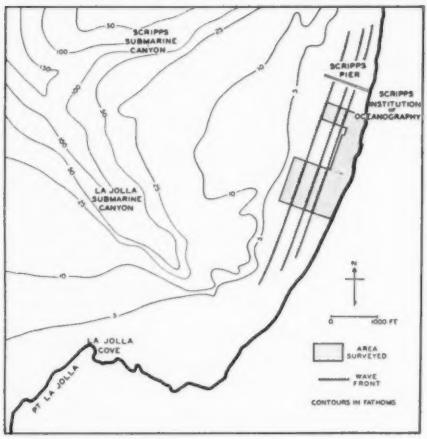

FIG. 1.—Showing the area in which most of the investigations were undertaken. Nature of sea floor shown by contours.

After discussing with lifeguards the causes for surf rescues and making some preliminary observations along the beaches, Shepard[4] called attention to definite evidence of outward drag of swimmers in relatively narrow seaward-moving belts of water. These lanes of agitated water extending out at right angles to the beach are well known to lifeguards and to experienced swimmers but seem to have largely escaped the notice of scientists. They are known as "rip tides" or "sea pusses," but the name "rip current" was proposed as being more appropriate, and the term "rip" might also be used as an abbreviation, which removes the unfortunate tidal connotation of the popular term "rip tide."

[2] "The 'Undertow,'" *Science*, Vol. LXII (new ser., 1925), pp. 206–8.

[3] Walter C. Jones, "The Undertow Myth," *Science*, Vol. LXI (new ser., 1925), p. 444; Wallace Craig, "The 'Undertow,'" *Science*, Vol. LXII (new ser., 1925), p. 30; I. Brant, "The 'Undertow,'" *Science*, Vol. LXII (new ser., 1925), pp. 30–31; Davis, "The Undertow Myth," *Science*, Vol. LXII (new ser., 1925), p. 33.

[4] "Undertow, Rip Tides or Rip Currents," *Science*, Vol. LXXXIV (new ser., 1936), pp. 181–82.

These rip currents were described as moving outward both at the surface and underneath the surface, so that they are something quite distinct from the supposed undertow. Subsequently, O. F. Evans,[5] on the basis of observations with colored water in lakes, showed that with an onshore breeze water may move shoreward at the surface and return underneath, thus suggesting the reality of undertow under conditions of an onshore wind. Evans' suggestion that such subsurface-return currents, while inconsequential in his experiments, might attain dangerous proportions, led to observations by Shepard and La Fond[6] which showed that at the Scripps Institution pier during strong onshore winds no appreciable undertow could be discerned but that the water moved principally alongshore both at the surface and near the bottom. Observations made by the writers subsequently have failed to produce any confirmation of the idea of dangerous undertow. While slow outward-moving subsurface currents may exist, the chief seaward return of water moved in by the waves seems to be in the form of rip currents.[7]

Recent investigations of the rips have shown that they are, in all probability, a phenomenon associated with all coasts where surf comes in more or less directly onto the shore. Surveys initiated recently by Emery have shown the erosional effects of these currents in shallow water. All the authors have combined in surveys to determine the nature of water movement in the rip currents. Also records compiled over several years by La Fond, Shepard, and others have been analyzed to find the relation of rip currents to other phenomena. The present report is an attempt to summarize the information obtained by these studies.

[5] "Undertow," *Science*, Vol. LXXXVIII (new ser., 1938), pp. 279–81.

[6] "Undertow," *Science*, Vol. LXXXIX (new ser., 1939), pp. 78–79.

[7] In an article to appear shortly in *Science*, O. F. Evans refers to undertow as a subsurface drift in various directions both landward and away from the land but in a direction opposite to the drift at the surface and existing at some distance from the shore. The existence of an undertow of this nature is not denied by the present writers. On the contrary, evidence could be supplied to show such counterposed drifts in the La Jolla district, although for the most part in directions alongshore. The writers have used undertow in the popular sense of a dangerous, subsurface current moving out from the shore under the oncoming waves.

GENERAL DESCRIPTION OF RIP CURRENTS

SURFACE MANIFESTATIONS

Rip currents, like double rainbows or sun dogs, are phenomena which are not seen by casual observers until they have been pointed out by someone familiar with them. However, after their characteristics are known, they can be easily recognized along shorelines where large breakers form. Rips are most readily identified by an

FIG. 2.—Showing a rip current extending out from the beach at Coronado, California. Note portions of other less pronounced rips on either side. Official United States Navy photograph.

observer looking down from an elevation, but careful scrutiny from the beach will also serve to show their presence. The following are their chief characteristics:

1. *Sediment-laden water.*—Rip currents located off a shore containing relatively fine sand or silt can be identified by a brown streak of water which protrudes beyond the breaker zone. This brown color is due to the sediment suspended in the water by the breaking waves and dragged seaward in the rip current. These brown streaks can be seen to move seaward spreading out as they go. New belts join them from time to time (Fig. 2).

2. *Green water.*—Shoreward of the main breaker belt one can often see a zone where the water has a distinctly greenish appearance. This color is due to the greater depth generally found along the course of a rip current. As will be shown later, the trend of these inner channels is likely to be diagonal to the shoreline.

3. *Foam belts.*—Where the bottom is rocky, so that the rip currents do not contain brown water, their presence may be observed by bands of foam which project seaward from the breaker belt (Fig. 3). Foam is also associated with the brown water and is often confined to the outer rim of an advancing rip.

FIG. 3.—Showing a rip current indicated by foam extending out from a rocky point without any beach.

4. *Agitated water.*—In a rip current the surface of the water is usually very much agitated, resembling in appearance a tidal current moving against oncoming waves. This agitation cannot only be seen but can be heard and felt both by a swimmer and by an oarsman rowing through the outer tongue of a rip current. Beyond the breakers the irregular waves in the rip sometimes have the appearance of whitecaps. According to reports of lifeguards, the water in a rip may be so choppy as to make breathing very difficult.

5. *Gap in advancing breakers.*—While waves do break in the rip-current zones, they often break much nearer shore than on either side, so that it is a common thing to see an advancing breaker with a gap at the point where the rip current is moving seaward (Fig. 4). However, a gap in the breakers does not necessarily show the presence of a rip current, since it may be due to a greater depth of the water along a belt where no rip current is operating or to interference of waves.

6. *Seaward movement of floating objects.*—When one is in doubt concerning the reality of a supposed rip current, drifting objects will often serve to test the case. For example, the existence of a rip was established where a stick floated out from the base of a 20-foot rock cliff directly against a storm wind and against large waves. Possibly such occurrences are common but have not been observed

FIG. 4.—Showing the gap in an advancing wave crest where a rip current is moving seaward.

because no one would suspect the presence of an outward-moving surface current at such a place. The drift of objects in typical rip currents will be discussed below.

WIDTH AND OUTWARD EXTENT

The maximum width and outward extent of rip currents cannot be determined until more data are available. Estimates made at Venice, California, by Mr. C. P. L. Nicholls[8] limited the outward projections to about $\frac{1}{2}$ mile. At La Jolla a convenient index is provided by the 1,000-foot Scripps pier. It is not unusual for a rip

[8] Supervisor of aquatics of the Los Angeles department of playground and recreation.

to extend beyond the end of this pier, and on some occasions they appeared to extend more than twice that distance from shore. From the cliffs along the San Simeon–Carmel coast highway, observations of rip currents suggested an outward extent of about a half-mile, under what were probably typical wave conditions. Since average wave conditions at La Jolla are accompanied by relatively short rip currents and large waves by greatly extended rips, it might be supposed that considerably greater lengths would accompany exceptionally large waves in this exposed San Simeon–Carmel area.

Rip currents are narrow near shore, commonly not over 50–100 feet across, but they widen farther from shore. Off La Jolla, beyond the breakers, they have been measured as being from 100 to 440 feet across. In the widest of these rips the current was especially concentrated in a belt 180 feet across. The rip currents observed from the San Simeon–Carmel highway appeared to have greater width compared to length than those seen at La Jolla or off other sandy beaches. The former were probably over 1,000 feet across. It was noted that all the currents are sufficiently narrow near shore so that swimming out of them should not be difficult, but a longer swim would be required beyond the breaker belt. However, currents in the outer zones are not so strong.

RELATION TO COASTAL AND SHORELINE CONFIGURATION

The statements from lifeguards regarding rip currents refer exclusively to areas where there are long, relatively straight beaches such as the one south of Scripps Institution (Fig. 1). However, investigation has shown that the currents are by no means confined to shores of this type. As far as could be determined, rip currents are found off all types of coasts where waves pound in more or less directly against the shore.

Relation to indentations.—Rip currents are found in many cases off the center of small beach indentations. In rare cases these indentations are reported to be the result of drains entering the sea at that point, but in general they are due to natural causes and processes which allow them to shift in position. Rips are also observed in larger coastal indentations. In the cases where there is no prevailing longshore current, they generally move out at the center

of the indentation, or they form on the downcurrent side of the bay where strong drifts exist.

At La Jolla Cove (Fig. 1) large waves do not ordinarily occur, but under some conditions resonance or some type of interference causes the building-up of a series of large waves, and these waves sweep into the cove with great force. After a series of waves of this type, a current is observed moving out from the rocky point which lies east of the cove.

Relation to rocky coasts.—An example has been referred to previously (Fig. 3) where a rip developed off a rocky coast where there was no beach. Other cases were observed along the mountainous coast of the San Simeon–Carmel highway. There are also a few rips off the rocky cliffs of Point Loma near San Diego. However, it is likely that rips are less common on rocky coasts than off sand beaches. Examination of the two types on the same day revealed fewer rips off the rocks. On the other hand, it should be borne in mind that it is not easy to recognize the rips where there is no bottom sediment to be thrown into suspension to indicate the outward movement beyond the breakers.

Relation to artificial structures.—Rip currents are frequently found running seaward along piers and groins. The slight deflecting influence of a pier evidently plays an important part in localizing these currents. At many beaches guards have posted warnings for bathers to avoid the vicinity of these structures largely because of the dangerous rips.

NATURE OF CURRENTS

Surface movement.—Investigations at La Jolla have given some information concerning the movement of water particles in what appear to be typical rip currents. Conversations with lifeguards have confirmed these observations. Figure 5 gives what is believed to represent typical movement of water in one of these rip currents. It can be seen to consist of three main parts, which have been called the "feeders," the "neck," and the "head." Just outside the beach there is a flow of water nearly parallel to the shore. An object drifting in this feeder current is carried in a path diagonal to the shore into the main outward-flowing current, or the neck, which moves essentially at right angles to the general coastal trend. Ordinarily

the water coming into the neck enters from a feeder on either side, although one current may flow more swiftly than the other. In these feeders, currents have been observed to move at about 2 miles an hour, although higher velocities may exist during storm waves. Water enters the neck not only from the feeders but also to some extent from the sides farther out.

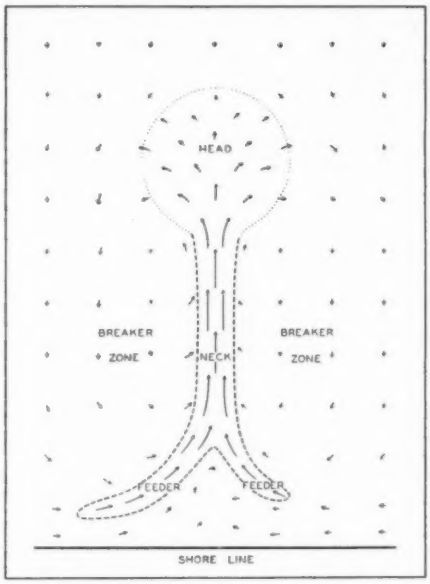

FIG. 5.—Diagrammatic sketch of a rip current showing its component parts and the common association of currents with it.

In the inner portion of the neck, shoreward of the point where the large waves break, current velocities are high, but the current becomes more intermittent in character because of the effects of the breaking waves. With each advancing wave the outmoving current is checked or may be given a strong side motion. After the crest has passed, the outward flow is resumed. In the outer portion of the neck the counteracting effect of large breakers is particularly noticeable. Frequently the forward surge of the waves completely interferes with the seaward passage of a floating object which simply moves back and forth until it is thrown out of the rip by a lateral movement of the current. As will be shown subsequently, this is the most dangerous position for a swimmer, particularly if he is trying to get out of the neck on the side from which the main current is moving (Fig. 5). According to Mr. T. V. Warren,[9] the currents may enter the neck

[9] A lieutenant in the Los Angeles County Lifeguards, who has had twenty years of experience with rip currents.

from both sides so that a floating object may be held within the neck until a pause in the onslaught of the breakers allows it to move outward. Also, on two occasions it was observed that, with small,

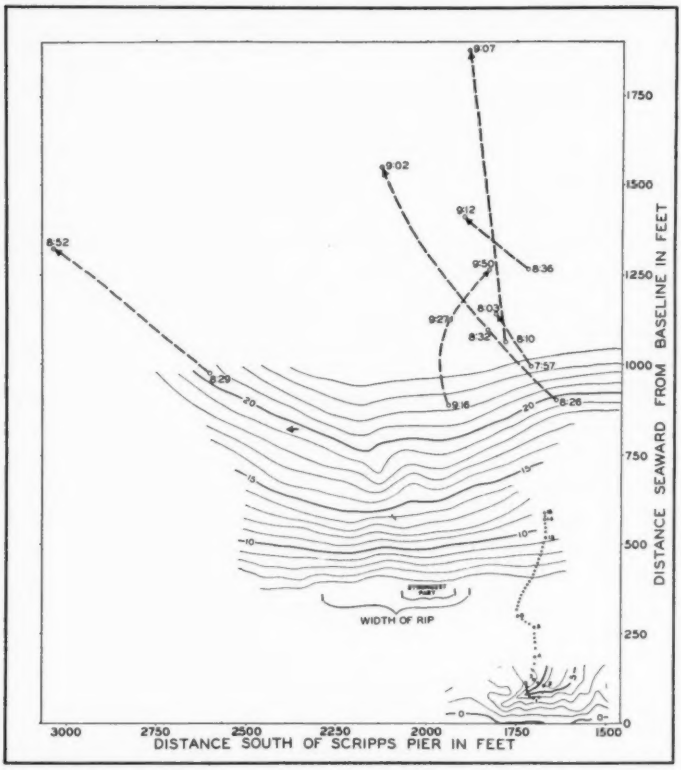

FIG. 6.—Showing the direction and speed of floating objects observed in rip currents south of the Scripps Institution pier. Shows also the contours of the bottom determined subsequently from the same area and during times of strong rip currents. The near-shore channel was surveyed on the day subsequent to the survey of the outer portion. Dotted line shows motion of a float submerged 2 feet below the surface. Time refers to clock time for the surface objects and to minutes from start in the case of the float. Contour interval 1 foot. Soundings are reduced to mean lower low water.

short-period waves accompanying an onshore wind, floating objects moved through the breakers without much delay.

A floating object which is thrown out of the rip at the neck moves shoreward and then is caught by one of the feeders and carried seaward once more. In moving seaward the path weaves back and forth under the influence of the oncoming breakers. A piece of kelp may describe several circles before being carried up onto the beach or carried seaward through the neck. Lieutenant Warren informed the writers of cases where lifeguards in making a rescue had also been forced into the same circular path, so that they went through the rip several times before making their escape.

In the outer portion or head of the rip current the water spreads out, and the rip becomes much wider (Fig. 5). Observations of the surface currents in the head were made from rowboats in the vicinity of the Scripps Institution pier. Paths of floating objects, both on the sides of rip currents and within them were plotted (Fig. 6). It will be noted that the general direction of movement was outward, but ample evidence of longshore movement away from the rip was seen on either side of the main current. At a distance of about 900 feet from the shore an outward movement of $\frac{1}{2}$ mile an hour was observed. Other objects moved outward respectively at $\frac{1}{3}$ and $\frac{1}{5}$ of a mile an hour.

To find the lateral extent of the rip, three objects were set adrift over a width of 350 feet along a line about 900 feet from the shore. Only one of these was thought to be definitely in a rip current, but all of them drifted outward, showing that the effect of the rip was much more widespread than was supposed. Another object set out on the south side of the head of a rip current was observed to move southward at first. Returning to the locality after observing other floating objects, we were unable to find the south-drifting float. Later it was picked up on the beach about 400 feet south of where it had been set out. Presumably it had described an arc and turned toward shore.

Along the side of an advancing head, eddies are often observable (Fig. 7). These whirls turn to the right on the right side of the rip and to the left on the left side. A turning movement is also experienced in a rowboat allowed to drift in the advancing end of a rip current.

Subsurface movement.—The movement of currents beneath the surface has not yet been completely explored either in rip currents or in breaker zones on either side. According to Lieutenant Warren, the flow may be stronger either at the surface or underneath. It is

FIG. 7.—Showing the curling edges of an advancing rip current. Note that a new addition to the current is moving out from the shore. Official United States Navy photograph.

his observation that where the neck is very narrow the flow underneath is stronger than at the surface and where the rip is spread over considerable area the flow decreases with depth. The presence of gullies in the sand (to be described later) underneath the feeders and the neck testify to swift movement where the rip is confined. Also observations from the Scripps pier[10] showed that rip currents,

[10] Shepard and La Fond, "Undertow," *Science*, Vol. LXXXIX (new ser., 1939), pp. 78–79.

evident at the surface, were also operating along the bottom in a depth of 5 feet of water. In another rip the outward movement along the bottom was found to be limited to a depth of 6 feet, although the outward movement at the surface continued more than twice as far from the shore to a point where the water was 16 feet deep. At another time current measurements were being made at the end of the Scripps pier in water about 18 feet deep, when a rip current was seen to move out over the spot where the measurements were in progress. Since the current meter near the bottom recorded continuous movement parallel to the coast while the current at the surface was moving seaward, it was evident that the rip had passed over the bottom water. Further indication that the currents do not reach great depth is derived from the fact that soundings show the absence of important channels along the bottom out beyond the neck of the rip current (Fig. 6).

The observation that floating objects are ordinarily carried out the neck of a rip current only to the point where the larger waves break, while the rip itself is seen to extend well beyond the breakers, indicates that there must be a greater transfer of water outward beneath the surface than at the surface. To test the nature of this subsurface current, large crossed vanes were suspended from a float to a depth of about 2 feet from the surface. A flag was placed on the float so that its motion would be observed. Since the movement would be more dependent on the pressure against the vanes than against the small float, the motion would be indicative of the subsurface current. The apparatus was put into a feeder channel of a rip current. After some lateral movements caused by oncoming breakers, it moved with a velocity of nearly 1 mile an hour out through the breaker zone and continued seaward beyond (Fig. 6). This movement was in contrast to that of kelp, which is often held up in the breakers as explained above.

On the other hand, it should not be supposed that this greater velocity just below the surface produces any appreciable tendency to draw a swimmer beneath the surface. Observations by the writers are supported by information from lifeguards showing that, while a swimmer's body may be tilted by the subsurface flow, there is little if any tendency to be pulled under the surface.

CHANNELS IN UNDERLYING SAND

The existence of channels in the sand along the path of a rip current has long been observed by lifeguards. Their presence was reported by all guards with whom the writers have talked. Surveys of these channels were initiated after a chance discovery of one several feet deep off the Scripps Institution. Several surveys of that channel were made and subsequently of other channels along a stretch of beach extending for $\frac{1}{3}$ of a mile south of the Scripps Institution.

Methods of survey.—Since the inner portion of a rip current is within the breaker belt, surveying of the bottom is very difficult. Some attempts were made to take soundings from a rowboat within the breaker belt, but this proved to be both difficult and dangerous, and the results were somewhat uncertain, particularly since it was found to be hard to concentrate on the work sufficiently to judge average wave levels.

A more successful method for the breaker zone consisted of wading and swimming out along prepared ranges on shore to cross ranges along the Scripps pier. The depth was determined by observing the water level on the surveyor's body. Help given the project by Dr. Roger Revelle was particularly valuable in this connection, since Dr. Revelle has a height of 6 feet, 4 inches.

Seaward of the principal breakers and to some extent within the belt, wire soundings were made from rowboats and depths determined with the usual sounding sheave. In the wading-swimming surveys, periods of low tide were chosen, while periods of high tide were picked for the boat surveys so as to have the least interference from breakers. The tide corrections were made after the surveys. Probably errors of as much as $\frac{1}{2}$ foot were due to the uncertainty as to mean level between the trough and crest of waves. Also, in studying the charts illustrating these gullies, it should be borne in mind that the outer portions were ordinarily not surveyed on the same day as the inner channels. Possible changes of depth may have intervened.

Relation to breaker zone.—The soundings and contours in Figures 6, 8, 9, and 10 will show the nature of the channels which are related to rip currents. Figure 8 indicates the possibility that the channel may continue out beyond the breakers. However, the sounding

data were scarce outside, and there is no definite proof of the existence of the outer channel. Furthermore, in a more extensive survey shown in Figure 6, the outer portion, which was in an intensive rip

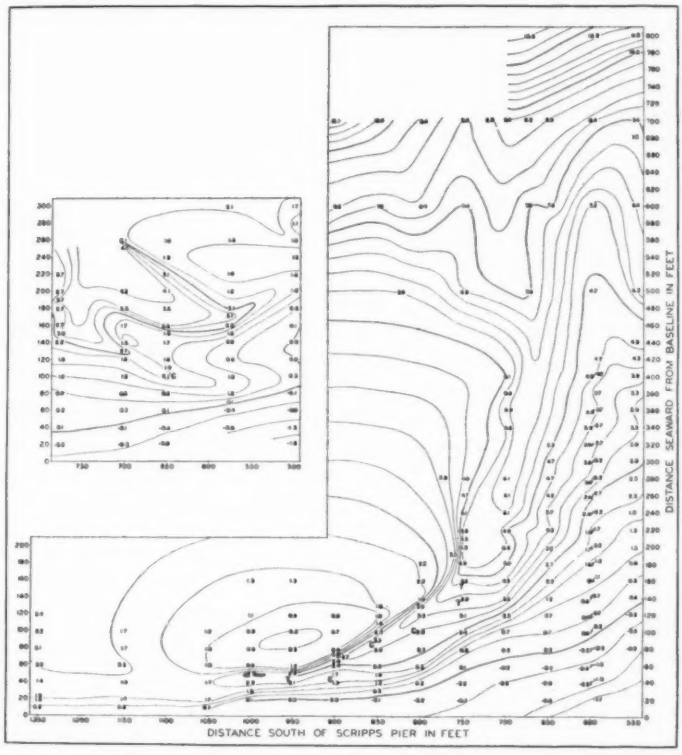

FIG. 8.—A survey of one of the channels associated with a rip current. Note the curving feeder channel extending into the neck. The inset shows a resurvey of a portion of the same area made after an interval of 12 days. Note that in the inset the feeder channel enters from the north rather than from the south. In the main diagram the two sets of soundings along the range 600 feet from the pier were made on successive days, with those on the left made first. The symbol *T* indicates the presence of terrace material on the channel floor. The symbol *C* indicates the presence of loose cobbles. Soundings are reduced to mean lower low water.

head, had no clear indication of a channel. Therefore it seems likely that the channels are features largely confined to the breaker zone.

Character of the channels.—Some of the channels are developed only in the neck of the rip current, but most of them have one arm which is located on the side of the feeder current having the greater velocity. These feeder channels are found so near the shoreline at low tide that a child may step out from the beach and fall directly into water beyond its depth. In Figure 8 it will be seen that one of these channels ran parallel to the shore for 200 feet. Seaward of the channel the water was very shallow above a bar. The term "ball and low"[11] might be applied to the bar and adjacent channel. During the survey a very conspicuous current was moving along this channel toward the outer trough. Also there was a weaker current moving south along the shore on the other side, but no feeder channel appeared on that side.

In Figure 8 it will be seen that the steeper side of the inner channel is toward the breakers. It happens that this is the inside of the curve which is contrary to the usual steep side in a land gully. However, in another case (Fig. 9), the shoreward side of the channel proved to be the steeper, so that no rule can be established regarding this steepening.

The channel in Figure 9 is cut to a depth of about 3 feet below its surroundings with the deepest entrenchment near the point where the channel assumes an outward direction. It will be seen that beyond this point there is a gradual decrease of the depth of the channel below its surroundings.

The floor of most of the channels was found to be decidedly irregular, so that it was difficult to walk along them for this reason as well as because of the strong current. In some of the channels there was a series of disconnected basins (Fig. 9) having a depth of half a foot or more below their sills.

Hard bottom.—The bottom of the inner channels off the Scripps Institution was found to consist in part of the same Quaternary terrace alluvium that is found in the low cliffs inside the area investigated. Since the channel shown in Figure 8 headed off a gully in the land cliffs, it was thought possible that it might be following an old submerged stream course that had been re-excavated by the

[11] D. W. Johnson, *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, 1919), p. 486.

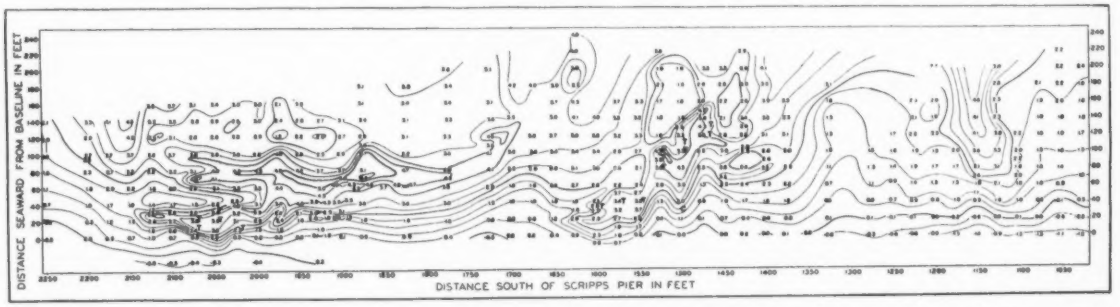

FIG. 9.—A survey of rip-current channels in an area to the south of that in Figure 8. The irregular bottom is thought to represent a stage in the fill of the channels. The symbol *T* indicates the presence of terrace material on the channel floor. The symbol *C* indicates the presence of loose cobbles. Soundings are reduced to mean lower low water.

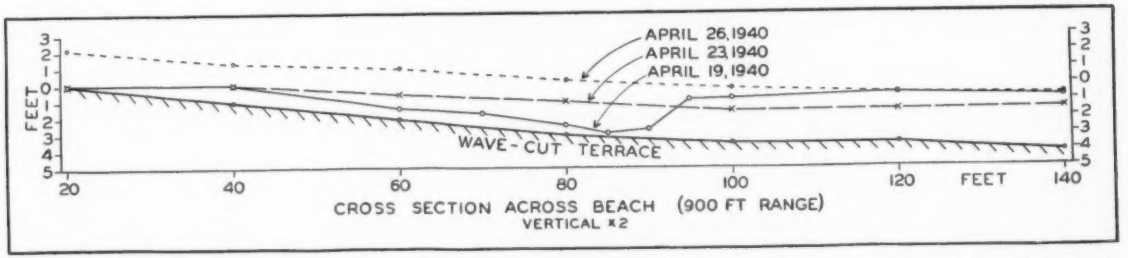

FIG. 10.—Cross section showing the relation of a feeder channel to the underlying wave-cut terrace on three occasions. Note that the channel became eliminated by April 26. Soundings are reduced to mean lower low water.

rip current. However, probing of the sand showed that the rip had not excavated below the level of the wave-cut terrace (Fig. 10) and that the relation of the channel to the land gully was only coincidental. The presence of fresh animal borings[12] in the terrace material of the channel bottom confirmed the absence of any excavation by the rip current into the underlying material.

FIG. 11.—Showing the channels appearing at a very low tide on Mission Beach, where rip currents had been operating. Photo by Captain C. W. Hardy of the San Diego lifeguards.

Shifting of the channels.—There are some places where permanent rip currents are said to exist, and, therefore, more or less permanent channels can be expected. These rips are controlled by some artificial structure such as a pier, a groin, or in some cases the entry of a drain. At Scripps Institution the rip currents were found to vary in position considerably. Also successive surveys showed relatively rapid changes in the position of the accompanying channels.

The changes in such a channel are illustrated best in the cross sections of Figure 10. Another illustration of such a change is seen

[12] The freshness of the borings is indicated by the presence of live *Exosphaeroma amplicauda* within the holes.

in Figure 8 in the inset showing a resurvey of a portion of the area of Figure 8. It will be seen that here the feeder channel is entering from the north, while in the main portion of Figure 8, based on a survey made 12 days earlier, it was entering from the south. It is notable that the main feeder current had also changed direction, showing the clear relationship between the currents and the channels. Three days after the survey of Figure 8 inset, the inner channel had completely disappeared and no appreciable rip could be observed in the locality.

By repeating the surveys some idea of the history of development and of the changes in the channels was obtained. It seems likely that in the earlier stages of channel development the bottom is relatively smooth and slopes outward more or less continuously as in Figure 8. Later, when the currents are less pronounced, bars develop along the course of the channels, and the outward continuity is lost. This stage is illustrated in Figure 9. Small, somewhat circular holes in the beach are the only remnants of the channel at a later stage. These are sometimes exposed at low tide (Fig. 11).

RELATIONSHIP TO OTHER PHENOMENA

GENERAL

Daily records have been kept for several years at the Scripps Institution showing the character of the waves and the nature of the currents. During one year the height of the sand under the pier was measured daily at forty-five stations, and during five years it has been measured at periods varying from semi-weekly to weekly.[13] Also for many years the pier has been a tidal station of the Coast and Geodetic Survey, and other records, such as water temperature, wind velocity, and rainfall, have been recorded. In addition, since November, 1938, the height of the sand at various points south of the Scripps Institution pier has been measured at intervals varying from daily to weekly. During more than one year, rip-current intensity was evaluated daily along the beach south of the Institution. While the evaluation is probably none too exact, it seems likely that important relationships can be drawn between the values given to

[13] Shepard and La Fond, "Sand Movements along the Scripps Institution Pier," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 272–85.

rip-current intensities and other conditions for which a numerical value can be given.

RELATION TO WAVES

Records at La Jolla.—Undoubted relation between intensity of rip currents and height of waves has been found from the records maintained at the Scripps Institution (Figs. 12 and 13). It was first shown by daily notations made for approximately a year in connection with the sand survey of the Scripps pier. These records, however, were made by various workers and are subject to a personal equation that makes them uncertain in value. A more systematic record was started by the writers in February, 1940, and is still in progress. The daily measurements of wave heights obtained on a wave machine[14] during this period are compared with the rip-current evaluation in Figure 13. It will be noted that the rip currents increase with every period of large waves, so that the largest values for rips correspond with the largest waves.

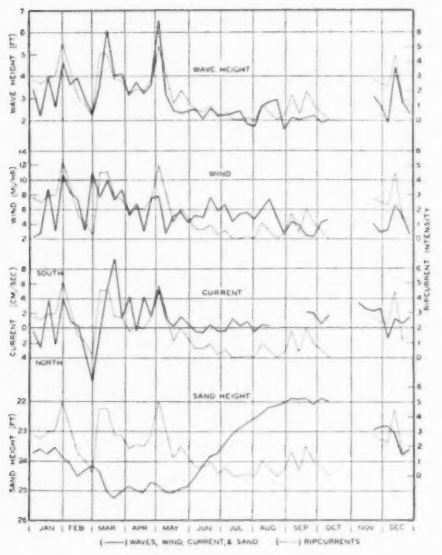

FIG. 12.—Showing the relation of rip-current intensity to wave height, longshore currents, wind, and sand height based on observations at the Scripps Institution during 1938. The data were obtained daily but are plotted as weekly averages.

Besides the height of waves, the period between crests and the smoothness of the wave records were examined to see if these characteristics had any bearing on rip-current development. It was found

[14] *Ibid.*, Pl. I.

that in general small waves were more choppy or irregular in their form and had slightly longer periods between major crests than the large waves. As a result, the smooth waves because of their size would be accompanied by larger rip values. However, it is possible to determine whether the smoothness and the period of the waves were important in development of rips in the few cases where rip currents did not follow wave height with much fidelity. The result

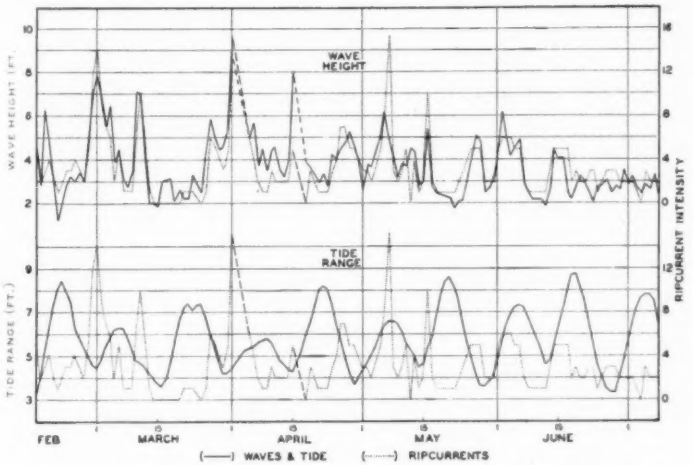

FIG. 13.—Showing the relation of rip-current intensity to wave height and tidal ranges at the Scripps Institution in 1940. These observations were made daily and are plotted as such. The high points on the tidal curve indicate spring tides and the low points neap tides.

of this comparison showed that there is no pronounced relation between these wave characteristics and the rip evaluation.

Wave and rip variations along different coasts.—Along the coast south of the Scripps Institution (Fig. 1) there is a distinct variation in the size of the waves. In the vicinity of the Institution the waves are relatively large, but to the south inside the head of the La Jolla submarine canyon the waves are almost invariably smaller. Still farther south, despite the protection of La Jolla Point, the wave size increases. Rips are largest somewhat to the south of the Scripps Institution but are negligible inshore from the submarine canyon.

South of the canyon rip currents of large size have been observed during periods of particularly large waves. The same relationship between the smaller waves and absence of rips landward of a submarine canyon is shown in air photos of the shore at the head of Monterey Canyon.

Observations along the outer exposed coast south of Carmel, California, were made on the same day as observations along the somewhat protected but otherwise similar coast of Santa Monica Mountains. Along the former there were large breakers, but along the latter only small waves were rolling in. Off the mountainous coast with the large waves there were impressive rip currents, whereas no appreciable rips could be distinguished along the mountainous coast with small waves.

Similarly, along the east coast of the United States the rip-current phenomena appear to be uncommon in the calm embayments of the Maine coast.[15] However, there are reports of these features (called "sea pusses") along the unprotected shorelines of New Jersey.

Relation to wave fronts.—The typical form of a wave front coming in to the shore south of Scripps Institution is shown in Figure 1. It will be noted that the wave front is relatively straight and the coast is broadly indented. It has been found that the rip currents are ordinarily greatest at the middle of the indentation. The waves come in most directly onto the coast in this section, while they are somewhat diagonal to the shoreline on either side. A similar relation to indentations of smaller scale has been referred to above. Possibly also the usual absence of rip currents along the Santa Monica Mountain coast and their presence at Venice and Playa del Rey farther south may be due to the fact that the waves come in more diagonally along the Santa Monica Mountains than they do farther south.

RELATION TO CURRENTS

The relation of the rips to the currents measured at the end of the pier is shown in Figure 12. The weekly averages which are shown in the 1938 series of measurements decidedly indicate that the rip

[15] On the other hand, tide rips, which are actually due to the tide, are very pronounced along many of the narrow passages of the Maine coast. Rip currents also exist on the open coast. One was observed along a rocky promontory at Deer Isle, Maine, during a storm.

currents vary with the direction and intensity of the currents at the pier end. The periods of currents flowing to the south are in general those of strong rips, whereas the periods of northerly currents correspond with weak rips. This relationship is less impressive where the more exact rip-current data of 1940 are compared with the daily record of the currents at the pier end. However, even in this record, the change from north-flowing to south-flowing current shows in general an increase in the rip currents. In a number of instances the rips show a growth when a north current slackened, in spite of the fact that the waves had subsided from their peak. Examples of this relationship are to be seen on March 10 and May 7.

On the other hand, the relation of the current to the rips in both records is decidedly less constant than is the relation of the wave height to the rips. Thus we find large waves and large rip currents on April 26, despite a decided northward current. On May 12 the relationship of rips to current direction is also reversed from the normal, but in this case the relatively large waves had no rips associated with them, so that neither influence appears to have played a part.

An unfortunate feature of the current record prevents a completely satisfactory correlation with the rip-tide evaluations. The current meter at the end of the pier has to be taken out of the water during excessively large waves in order to preserve it from damage. Therefore, the nature of the currents on days when the rips are especially large is not well known. Future direct observations may remedy this condition.

RELATION TO WINDS

Indirectly the rip currents are related to winds, since winds produce most of the waves. However, along the coast of southern California, the large waves appear to come largely from storm centers at a considerable distance from the coast. Frequently large waves roll in accompanied by no appreciable wind. Also, the period of relatively strong winds at La Jolla extends somewhat longer into the late spring than does the period of large waves. The rip currents subside with the large waves, and strong rips do not occur on the windy days of late spring and early summer when the waves are small.

On the other hand, the rip currents may be distinctly related to the direction of the wind. Rip currents appear to be small when the wind is blowing along the coast. A good example of this was observed near San Simeon, California. To the north there was little wind blowing, and large rips were in operation; but to the south, where the land juts out at Point Piedras Blancas, the wind was blowing violently along the coast, and rip currents were inconspicuous. However, on one occasion, rip currents were observed at La Jolla when there was a strong longshore wind, but in this case heavy runoff due to a violent rain was piling up water along the shore and supplementing the effects of the breaking waves.

RELATION TO TIDES

Since the tides produce currents, it might be supposed that the rips would be stronger at spring tides, when these tidal currents are at their maximums. However, a plotting of the daily tidal range in the same curve with the rip-current evaluation shows that the rips have no evident relation to the spring and neap tides (Fig. 13). The cases where the wave-height and rip-current curves are at slight variation are not explicable on the basis of tides.

In one way, however, the tides may have some influence on rip currents. During low tide the water is sufficiently shallow to concentrate the flow of the current within the rip channels, whereas the deeper water at high tide is less confined by the channels. Observations at the Scripps Institution give the impression that rip currents are more pronounced at low tide. On the other hand, in a paper by C. P. L. Nicholls,[16] the statement is made that "it is usual for the rip tides to disappear at low tide, and it is likely that most rip tides will occur at high tide." Whether this inconsistency is due to a difference of locality of observation is uncertain.

RELATION TO CUT AND FILL OF BEACHES

The numerous measurements of sand height along the Scripps Institution pier[17] and along the beach to the south of the Institution

[16] "Rip Tides and How To Avoid Their Perils," *Calif. Beaches Assoc.*, Vol. I, No. 9 (1936), p. 12.

[17] Shepard and La Fond, "Sand Movements along the Scripps Institution Pier," *loc. cit.*

afford another check on the various influences on rip currents. The times of year when the sand is cut low along the inner portion of the Scripps pier are also times when the rip currents are strong, while the times of high sand along the inner pier correspond with times of weak rips (Fig. 12). However, this correspondence may be explicable purely on the basis of wave size, since the large waves of winter produce cutting of the sand and the small waves of summer produce fills. Furthermore, large waves are accompanied by large rips, whether or not the beach is cut away. On the other hand, there is reason to believe that the locations of the principal rip currents near the Scripps Institution are associated with beach indentations and thus with sand level at these places. For several years it has been found that the beach is cut to its lowest level for the year off the Institution several months later than in a zone about 1,000 feet to the south. The rip currents also appear to be somewhat larger off the southern zone at an earlier date and off the Scripps Institution later.

ORIGIN OF RIP CURRENTS

PREVIOUS SUGGESTIONS

In describing a phenomenon which he called "undertow" but which was clearly a rip current, M. P. Hite[18] referred to the piling-up of water along the shore behind a submerged bar and to the return of this water along channels. Nicholls[19] attributed rip tides to any features which "break up this littoral current resulting in variance in the ocean bottom." He also states: "Rip tides usually are caused . . . . by converging currents." These opinions are upheld by the present investigation.

INADEQUACY OF UNDERTOW

The common landward movement of floating objects[20] and the rapid movement in that direction in the breakers show that the surface water over most of the area is moving landward. This mo-

[18] "The 'Undertow,' " *Science*, Vol. LXII (new ser., 1925), pp. 31–33.

[19] *Op. cit.*, p. 12.

[20] T. Levi-Civita, "Über die Transportgeschwindigkeit einer stationaren Wellenbewegung," *Vorträge aus dem Gebiete der Hydro- und Aerodynamik* (Berlin, 1924), pp. 85–96.

tion may be compensated either by a return seaward in the form of undertow along the bottom or as a concentrated outward flow of surface and near-surface water as a rip current. The prevalence of rip currents shows that the return is largely by the second method. The reason for the dominance of the rip currents is that undertow is impeded by two factors. In the first place, there is more friction along the bottom so that outward flow is easier at the surface. Second, sea water is stratified to a certain extent with the heavier water underneath. As a result the light surface water cannot displace the water in this heavier zone. The effect of density stratification, however, cannot be important in the breaker zone where the water must be quite thoroughly mixed, but in the head of the rip beyond the breakers this factor may be very important. The frictional effect is evidently of considerable importance in the breaker zone, since near-shore observations along the Scripps pier have shown that objects in suspension near the bottom of a rip do not move outward nearly so fast as objects near the surface.

CHANNELS AS A CAUSE OF THE RIP CURRENTS

While there can be little doubt that groins and piers are an important cause of rip currents, as stated by Nicholls,[21] the relation of channels in the sand as a cause of these currents is not so clear. Rips have been observed in the absence of channels. Also the longshore channels or lows are found in the absence of rips. On the other hand, the channels associated with necks of the rip currents have not been observed as yet without currents.

Investigations of ball and low along the Scripps Institution pier have shown that these longshore channels and bars are developed principally as an accompaniment of longshore currents and may form under conditions of either small or large waves. During the development of the phenomenon the chief process appears to be the excavation of the low rather than the building-up of the ball. According to Lieutenant Warren,[22] such channels grow in length in the direction of the prevailing longshore currents until they make contact with a minor gap in the ball. This gap serves as a means for the water moving alongshore in the low to escape sea-

[21] *Loc. cit.*

[22] Personal communication.

ward, forming a rip current. Thus the low becomes also a feeder channel of a rip current. This rip current presumably deepens the initial gap and forms the outward-trending channel beneath the neck of the rip current. The more pronounced the channel, the more the rip tends to remain in this place.

It seems likely that the channels are caused primarily by the rip current, although an initial shallow indentation may localize the rip, as is shown by the channel on the right of Figure 9, which was not present a few days earlier in the survey shown on the left of Figure 8. The rapid filling of channels when conditions change, as above, shows the partial independence of rip currents from channel locations.

EFFECT OF CURRENTS AND WAVES

It has been shown that, in general, abundance of rip currents appears increased by southward-flowing currents as measured from the pier and decreased by northward-flowing currents. The cause of this relationship can perhaps be determined from an examination of the coastal configuration (Fig. 1). Relatively straight waves piling onto the broadly curved beach south of the pier should cause a northward transport at the south end of the beach and a southward transport at the north end. Such opposite movements tend to pile up water in the middle of the beach, producing rips. Thus times of southward currents at the pier should tend to correspond with periods of stronger rips in the middle of the beach.

Since the principal rips are found south of the pier, currents flowing to the south would feed these rip currents, whereas currents flowing to the north would tend to remove water from the rip area. Furthermore, a general longshore current flowing to the north does not meet with any obstruction which might lead toward the piling-up of water. The relative straightness of the coast continues for almost 100 miles in that direction. On the other hand, 1½ miles to the south the coast bends outward to form La Jolla Point, which may cause a piling-up of the water during times of south-flowing currents. This excess water may escape partly in the form of rip currents.

When once an outward-flowing current is initiated, it tends to weaken the breakers locally. The smaller the breakers along the

path of the rip current, the faster it can flow. Thus the rip current accelerates until the head of water onshore, which was due to the piling-up effect of the two opposing currents, has been sufficiently lowered so that the rip dies down awaiting the buildup of another head. This sequence accounts at least in part for the spasmodic flow of the rips (Fig. 7).

While the local longshore currents play an important part in the development of rip currents, the close relationship shown between the rip evaluations and the size of waves shows that the waves must be the dominant factor. The larger the waves, the more water is piled onto the shore, and, therefore, the more water has to return seaward. However, the height and trend of the waves are largely responsible for the development of the local longshore currents, so that these two factors are interrelated.

SIGNIFICANCE OF RIP CURRENTS

EFFECT ON BEACHES

Rip currents have both a direct and an indirect effect on beaches. Their direct effect is the production of channels and holes in the portion of the beach exposed at lowest tides. The indirect effect comes from the presence of indentations inshore from the channels which allow the waves to wash higher on the shore so that they may have more erosive action inside the rip current.

OUTWARD TRANSPORTATION OF SEDIMENT

Sorting of beach sands.—It has been generally assumed that beach sands become sorted by the breaking waves stirring the sand and the backwash carrying the fine material into the undertow current, which in turn carries the load seaward.[23] If undertow is eliminated as an important process, rip currents are still available as a means of carrying the fine sediments well beyond the beaches. In this process the wave-stirred sediment is carried along the feeders to the neck and thence beyond the effect of breaking waves.

As an example of the operation of this process observations made near the Scripps Institution may be cited. After the great southern

[23] See, e.g., C. R. Longwell, A. Knopf, and R. F. Flint, *Textbook of Geology* (2d ed.; New York: John Wiley & Sons, 1939), p. 200.

California flood of March, 1938, the beach beneath low cliffs south of the Institution was covered with a thin mantle of mud. After one or two high tides this material was largely removed from the beach. Much of it could be seen moving seaward in the large rip currents which were in operation. Samples taken along the Scripps pier showed that the mud had not lodged within a thousand feet of the shore. Similarly, after winter floods had carried large masses of muddy sediments down the slopes of the Santa Lucia Mountains onto the beaches, large rip currents were observed carrying the fine sediment seaward.

A source of offshore sediment.—The evidence given above indicates that rip currents carry fine material seaward, but their limited outward extent might be supposed to restrict them to near-shore zones as a transporting agent of sediment. Off southern California the chief sites of sedimentation are thought to be the offshore basins and troughs.[24] However, since the chief source of sediments for these basins must be the land, any process which can carry fine sediment out from the shore must be important. Furthermore, it should be remembered that there are other types of currents out beyond the zone where rip currents predominate, and the suspended sediment carried out by the rips must be transferred to a considerable extent into the offshore currents in which it may be carried to the various basins before settling-out of suspension.

An example of this ferrying of sediment from shore out into the main circulation was observed from the "E. W. Scripps" while anchored off the mouth of the San Dieguito River following the March, 1938, flood. Muddy-water zones were seen to move out from the shore in a series of pulsations with marked color boundaries at the front of each advancing mass. These outward-moving masses of muddy water closely simulated typical rip currents except that they had much more suspended sediment. However, the outward movement was presumably due to the piling-up of water by the entering river rather than by the waves; but, whatever the cause, these outward-moving masses were supplying the offshore currents with large quantities of suspended mud.

[24] Roger Revelle and F. P. Shepard, "Sediments off the California Coast," *Recent Marine Sediments* (Tulsa: Amer. Assoc. Pet. Geol., 1939), pp. 245–82.

POSSIBLE RELATION TO SUBMARINE CANYONS

As yet no one has attempted to show that rip currents are the cause of submarine canyons. However, this oversight may be due to lack of information concerning these currents. The concentrated outward flow of the rips on open coasts gives them a distinct advantage as a canyon cause over other known types of oceanic currents. Also, their associated gullies may serve to stimulate interest concerning possible relation between the rips and submarine canyons. Furthermore, the absence of large breakers at the heads of canyons and their presence on either side suggest the possibility that water piled up by the breakers might return seaward along the axes of the canyon. There is some evidence that currents do move toward the canyon heads.[25] Also the evidence accumulated in work on the "E. W. Scripps" has shown that where canyon heads approach the California coast little sedimentation has taken place on the canyon floors.

On the other hand, the importance of rip currents either as a cause of canyons or even as a means of keeping them clear of sediments appears unlikely for the following reasons:

1. The observations given above suggest that the currents do not extend more than a few feet below the surface.
2. The density stratification of ocean water must act as a serious impediment to deep circulation of such a current.
3. The rip currents are not known to extend outward more than about ½ mile, which is in great contrast to the submarine canyons which extend out for as much as 100 miles.
4. After the occurrence of large waves, with their accompanying large rips, examination of canyon heads has failed to show evidence of deepening.
5. Evidence given above shows that rip currents in the vicinity of La Jolla are much less pronounced around the head of La Jolla Canyon than they are on either side. Airplane photographs of the coast at the head of Monterey Canyon also show that there are rips on either side and an absence of rips at the canyon head.
6. The scoured condition of the canyon heads can be explained by the mud flows and other types of submarine slipping which are known to occur at these places.

[25] F. P. Shepard and K. O. Emery, "Submarine Topography off the California Coast: Canyons and Tectonic Interpretations," *Geol. Soc. Amer., Special Paper No. 31* (1941), p. 103.

Accordingly, the present state of our information gives little ground for connecting the submarine canyons with rip-current movements. Whether these currents may play some slight part in canyon development or in clearing out the canyon heads during unusually large wave periods remains to be seen.

A MENACE TO SWIMMERS

Lifeguards who have been consulted by the writers are of the opinion that rip currents are the dominant cause of trouble encountered by bathers. There appear to be two principal locations where swimmers get into difficulties. The first and most common location of rescues is in the rip-current neck (Fig. 5), at the point where the large waves are breaking. A bather may find himself in this position either by slipping into a feeder channel, which may be very near the shore, and being swept out into the neck or by jumping through breakers in the zone next to the rip-current neck and being pulled gradually toward the neck until, having reached the main channel, he finds that he is in water beyond his depth. Ordinarily a person getting into the neck will not be carried beyond the breakers, but the outward-moving current may prevent all but a very good swimmer from progressing landward. As a result, the victim finds he is being buffeted by each oncoming wave but is making no progress toward the shore. Furthermore, if he has slipped into the neck from shallow water along the side of the channel, his attempts to swim parallel to the coast back to shoal water may not succeed because the water may be moving toward the neck with considerable speed from that side (Fig. 5). The solution for a swimmer caught in this situation is to try to swim out of the rip to the side opposite that from which he entered the neck (Fig. 5). If he does not get out on one side, he should try the other. Probably there are times when this method would not succeed, since water may come in forcibly from both sides. In this case a good swimmer can go out through the breakers and escape as explained below.

The second situation of danger is beyond the breakers. A swimmer may have gone through the breakers in a rip current or may have swum into a rip while swimming along the coast outside of the

breakers. Turning toward shore, he may find that he can make no progress. The current in the head is not ordinarily very strong, but most swimmers are not very fast. In some cases the rip is of short duration so that only a little patience is necessary; but at other times the rip, even if somewhat pulsatory, continues to move outward over a long period of time. The solution for a bather caught in this situation can be seen from Figure 5. He should swim parallel to the shore and, after a relatively short distance, will be helped by the laterally moving current of the rip. Then, after getting out of the turbulent rip, in coming landward he will be further assisted by the shoreward-moving surface water next to the rip. Two possible difficulties may be encountered in attempting this procedure. Sometimes new rips develop adjacent to old ones, so that the swimmer might have to go a considerable distance parallel to shore before escaping. Another trouble may be that the swimmer having reached shallow water successfully may stumble into the feeder channel and be swept out into the neck of the rip in a fatigued condition. This last difficulty can be avoided by approaching the shore with caution and going around any feeder channel.

The dangers of rip currents are such that swimmers should exercise considerable precaution in their surf swimming. Careful scrutiny of the breakers will usually show whether there are dangerous rips present. Also the swimmer will do well to go out from broad projecting points rather than from beach re-entries where rips are most common. Particularly should he avoid piers and groins or other engineering structures which might deflect outward a longshore current. Since the danger exists only when the waves are large, bathing in summer is ordinarily free from such difficulties even on open coasts.

SUMMARY AND CONCLUSIONS

Along coasts where large breakers move landward over a shallow-water platform the cumulative landward movement of the surface water is compensated by seaward-moving lanes of water which extend out normal to the beach. These water masses, moving contrary in direction to the wave approach, are given the name "rip currents." According to available evidence they appear to take the

place erroneously assigned to undertow, in that they return the water which tends to be piled onto the beach by the waves and in doing this carry seaward fine sediment derived from the land.

Rip currents are ordinarily fed by water moving along the shore from either side. The two currents join and extend out in what is known as the neck, where the water rushes through the breakers in a narrow lane. Beyond the breakers the current spreads out in what is called the "head" and dissipates. The outward-moving columns can be recognized by their brownish color if they contain abundant sediment, by their agitated water, or by an extension of foam belts well outside the line of breakers.

These currents are ordinarily long and narrow, but in their outer zone they widen considerably. They extend out from a few hundred up to about 2,500 feet from the shore and vary from narrow belts 50 or 100 feet across in the feeders and neck to as much as 500 feet or more in the heads. Their velocity is known to be as great as 2 miles an hour in some instances. This rate of flow is very inconstant, being greatly checked or even stopped by advancing wave fronts. The flow is capable of erosion near the shore where it produces channels a few feet deep. These channels may change in location and in form in periods of a day or even during the change of a tide.

Rip currents are important as a means of transporting fine material from the shallow water along the shore into the main-current circulation outside a coast. They are also a considerable source of danger to bathers, since their velocity is such that a swimmer may not be able to make progress against them. Most rescues from the surf along the coast of southern California are made in these rip currents.

ACKNOWLEDGMENTS.—The writers wish to express their appreciation for the suggestions and interest taken in the work by Dr. H. U. Sverdrup and for the help provided on two occasions by Dr. R. R. Revelle in mapping the bottom beneath the currents. Also the help of various W.P.A. assistants in making daily records of rip currents is gratefully acknowledged.

THE TECTONIC SIGNIFICANCE OF SOME PEGMATITES IN NEW HAMPSHIRE

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ABSTRACT

Pegmatites genetically related to the Bethlehem gneiss (Mount Clough pluton) are abundant in west-central New Hampshire. Those within the gneiss itself are of three types: (1) segregation pegmatites, (2) shear-zone pegmatites, and (3) filled-fissure pegmatites. Pegmatites within the surrounding rocks are confined principally to a broad belt of schists of the Littleton formation on the east side of the gneiss. These have been controlled by the structure of the schist and occur as large, tabular bodies several hundred feet long.

A study of the filled-fissure and shear-zone pegmatites indicates that the foliation of the Bethlehem gneiss is a primary structure. Pegmatites in the Littleton schist indicate that the Bethlehem gneiss was intruded shortly after the main part of the folding and the development of the schistosity. The preponderance of pegmatites in the schist on the east side of the Bethlehem gneiss and the absence of such bodies on the west side favors the interpretation of the Bethlehem gneiss as a huge intrusive sheet dipping moderately to the east.

INTRODUCTION

Early in the course of a study of the igneous and metamorphic rocks of west-central New Hampshire no particular attention was paid to the pegmatites locally abundant in that part of the state. As field work progressed, however, it became more and more apparent that the pegmatites furnished considerable information which aided greatly the interpretation of the regional geology. It is the purpose of this paper, therefore, to describe these pegmatites and to discuss their origin and tectonic significance.

GEOLOGICAL RELATIONS

The greater part of the region studied is underlain by mica schist, amphibolite, quartzite, and granulite which represent metamorphosed sedimentary and volcanic rocks, ranging in age from Middle Ordovician (?) to Lower Devonian. These Paleozoic formations were folded, faulted, and metamorphosed and intruded by plutonic masses. The structural trend throughout most of the region is north northeast (Fig. 1).

The igneous rocks of the region are medium- to coarse-grained gneiss—ranging from quartz diorite to granite—and belong to two

distinct periods of intrusion. The rocks of the older or Oliverian magma series were intruded before the period of folding and metamorphism.[1] They occur in domelike bodies, several miles in length, with remarkably concordant roofs. The younger plutonic rocks belong to the New Hampshire magma series. They were intruded during the late stages of folding and shortly thereafter; and, as Billings[2] has shown, they played an important role in the metamorphism of the Paleozoic formations.

Numerous plutonic bodies belonging to the New Hampshire magma series have been mapped in the state, but only those bodies composed of the Bethlehem gneiss are of importance here. As seen in Figure 1, the Bethlehem gneiss occurs in elongated masses trending parallel to the regional structure. The contacts of the gneiss are strikingly conformable to the schistosity of the surrounding rocks not only in ground plan but also in cross section. These bodies are interpreted as sheetlike intrusives.[3]

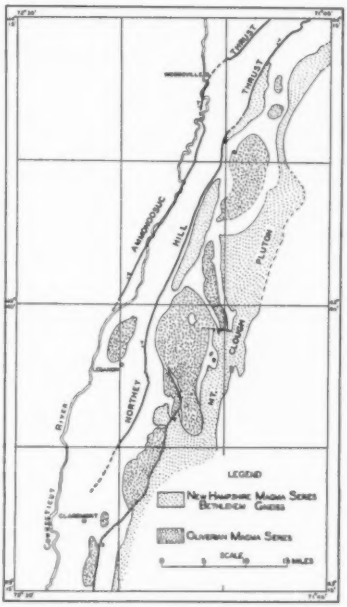

FIG. 1.—Structural units of western New Hampshire.

The present study deals with only one body of Bethlehem gneiss and its associated pegmatites. This body may be conveniently re-

[1] M. P. Billings, "Regional Metamorphism of the Littleton-Mooselauke Quadrangles, New Hampshire," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), p. 502; C. A. Chapman, "Geology of the Mascoma Quadrangle, New Hampshire," *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 146.

[2] *Op. cit.*, p. 557.

[3] Billings, *op. cit.*, p. 537; K. Fowler-Lunn and L. Kingsley, "Geology of the Cardigan Quadrangle, New Hampshire," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1939), p. 1376; Chapman, *op. cit.*, p. 163.

ferred to as the Mount Clough pluton (Fig. 1). Although not completely mapped, the length of the pluton is at least 70 miles; the width ranges from $\frac{1}{2}$ to 7 miles. Petrographically the gneiss ranges from granodiorite to granite and is composed of quartz, microcline, andesine, biotite, and locally a little muscovite. Very minor amounts of epidote, chlorite, zircon, apatite, magnetite, ilmenite, sphene, pyrite, rutile, and allanite are present. The rock is locally porphyritic with phenocrysts of microcline up to several inches in length, commonly partly replaced by myrmekite. The foliation of the gneiss is produced mainly by the parallel orientation of mica flakes.

The numerous pegmatites genetically related to the Bethlehem gneiss of the Mount Clough pluton are of two types: those occurring within the gneiss and those within the surrounding metamorphic rocks.

PEGMATITES IN THE GNEISS

Pegmatites within the Bethlehem gneiss itself may be classed as (1) simple segregation pegmatites, (2) pegmatites associated with small shear zones, and (3) filled-fissure pegmatites.

SIMPLE SEGREGATION PEGMATITES

Certain irregular bodies of pegmatite, a few inches to a few feet across, grade imperceptibly into poorly foliated gneiss. A coarse texture and lack of foliation seem to characterize these bodies. Mineralogically, however, they closely resemble the gneiss itself except for their low content of biotite. This mineralogical similarity between pegmatite and gneiss, the irregularity of outline of these bodies, and the gradational contacts strongly suggest they are segregation pegmatites formed by the local concentration of mineralizers in the late stages of crystallization of the gneiss.

Their marked irregularity would indicate that these bodies had formed in those portions of the gneiss where shearing stresses were weak. Otherwise the fluids from which they formed might have been squeezed out entirely or at least might have developed pegmatitic bodies whose shape shows some relation to the major or minor structures of the pluton. This interpretation is supported by the fact that the foliation of the gneiss in the vicinity of these pegmatites is poorly developed.

PEGMATITES ASSOCIATED WITH SMALL SHEAR ZONES

In certain areas pegmatites associated with narrow shear zones are numerous and very significant features (Fig. 2). The shear zones average 4 or 5 feet in length and are only a few inches wide. The numerous shear zones in any one locality strike closely parallel with one another. Their trend is across the foliation of the gneiss, usually at angles between 40° and 70°. The central portions of the zones are filled with pegmatitic material whose grain size is several times that of the inclosing gneiss. The material consists predominantly of

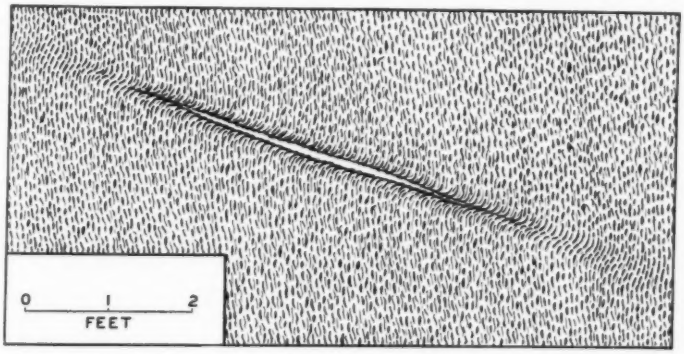

FIG. 2.—Sketch in plan view of shear zone and pegmatite in Bethlehem gneiss

quartz, microcline, and plagioclase. Muscovite, biotite, and black tourmaline occur in minor quantities.

From a study of the shear zones the movement appears to have been essentially horizontal, and the relative direction of shear along the zones may be determined by the way the biotite layers in the gneiss have been dragged around from their original position. The amount of drag progressively increases from outside the zones to the centers, where the trend of the biotite layers is parallel to the strike of the zones themselves. The pegmatite fillings pinch out along their strike, and the shear zones pass into simple "monoclinal flexures."

It is evident that the principle involved in the formation of these pegmatites is that of dilatancy. In the late stages of crystallization the Bethlehem gneiss consisted of a closely packed aggregate of crystals with an interstitial pegmatitic liquid. As the shear fractures

formed, narrow zones of loosely packed crystals were developed; and into these newly developed zones of potentially low pressure was drawn some of the pegmatitic fluid. Pegmatite veins or streaks, with somewhat gradational contacts, were thus formed. It may be observed in outcrop that where the shearing was most intense, as near the center of each zone, the pegmatitic streak is most pronounced. On the other hand, where the amount of shear was small, as near either end of a zone, there was little or no dilation, and the pegmatite pinches out.

These shear-zone pegmatites are probably contemporaneous with the simple segregation pegmatites already described, as they, too, formed from residual liquids derived from near-by portions of the crystallizing intrusive. They must have formed before the inclosing rock was completely solid and while it behaved somewhat as a plastic-mass, allowing the layers of biotite in the gneiss to be dragged around—in many cases, at right angles to their original position. This strongly favors the belief that the foliation of the Bethlehem gneiss is a primary structure.[4] The foliation must have developed before the rock had completely crystallized; it cannot be a secondary feature produced by dynamic metamorphism.

FILLED-FISSURE PEGMATITES

Many of the pegmatites form sharp-walled dikes or veins which cut cleanly across the foliation of the gneiss. They may be over 100 feet long and from 1 or 2 inches to 5 or 6 feet wide and are composed essentially of quartz, microcline, and plagioclase with minor amounts of muscovite, biotite, black tourmaline, garnet, and beryl.

The fact that these pegmatites occupy clean-cut fractures and each is of uniform width would indicate that they formed when the inclosing mass of gneiss was essentially solid. Furthermore, the orientation of the pegmatites with respect to the foliation and linear features of the gneiss suggests that the pegmatites filled diagonal and cross joints in the plutonic body. The fractures in which the pegmatites formed must have tapped pockets of residual liquid in the deeper parts of the igneous body. It may be concluded, therefore, that the filled-fissure pegmatites are younger than either the simple segrega-

[4] Billings, *op. cit.*, p. 537; Chapman, *op. cit.*, p. 162.

tion pegmatites or the shear-zone pegmatites previously described. Here, again, we have evidence that the foliation of the Bethlehem gneiss is a primary structure because the filled-fissure pegmatites, genetically related to the gneiss, show little or no signs of shearing, and yet they occupy fractures which cut sharply across the foliation.

Only one filled-fissure pegmatite was observed which showed the effects of later shearing (Fig. 3). This pegmatite is well exposed for several yards, where it shows a very sinuous trend and a great variation in width over short distances. It appears from a study of this

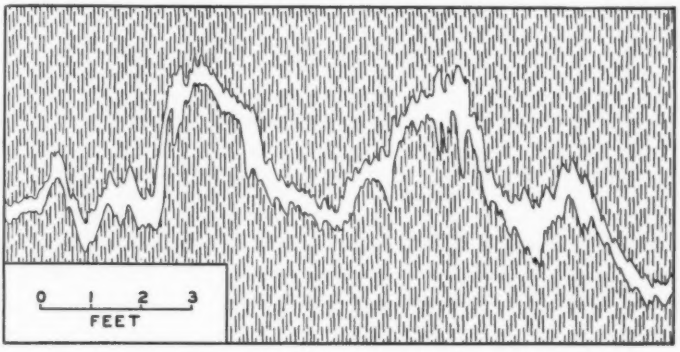

FIG. 3.—Sketch in plan view of sheared pegmatite in Bethlehem gneiss

outcrop that the pegmatite originally cut the gneiss as a sharply defined fissure filling but a few inches in width. The apparent thickening and folding were accomplished later by small displacements along the numerous planes of foliation in the gneiss.

One might at first be inclined to interpret this sheared pegmatite as indicating that the foliation of the Bethlehem gneiss was a secondary feature developed in a more massive rock. Such a conclusion does not seem justifiable, however, if one considers the rarity of this feature and the great number of unsheared pegmatites in the gneiss. It is not at all illogical to suppose that the planes of foliation in a primary gneiss are also planes of potential weakness and may serve as shear planes for "slip folding." If we conclude, therefore, as field facts in the surrounding area compel us, that the foliation of the Bethlehem gneiss is a primary structure, we may consider this de-

formed pegmatite as lying in an area of very localized shearing where deformation took place most readily along the planes of foliation. In this locality, therefore, the foliation is in part a primary and in part a secondary feature; the primary foliation served to direct the development of the secondary structure which parallels it.

PEGMATITES IN THE METAMORPHIC ROCKS

A broad belt of pegmatites in schist of the Littleton formation extends for many miles along the eastern border of the Mount Clough pluton (Fig. 1). Several of the individual bodies, such as those in the town of Grafton, have long been famous mineral-collecting localities. The pegmatites are usually tabular or lenticular and range up to several hundred feet long and many tens of feet thick. In most instances they have been intruded essentially parallel to the planes of schistosity, which dip, for the most part, 30°–60° to the east. In several places where the schistosity is nearly flat the bodies are essentially horizontal. K. Fowler-Lunn and L. Kingsley[5] report numerous flat pegmatites in this extensive belt which, throughout part of their extent, have followed nearly horizontal joint planes. Most of the bodies are typical granite pegmatites composed essentially of quartz, microcline, albite (in part cleavelandite), and muscovite. Black tourmaline, biotite, garnet, beryl, and numerous other rarer minerals are locally present. The surprisingly great number of pegmatites in the surrounding Littleton schists suggests that the magma which crystallized to form the Bethlehem gneiss was heavily charged with water and other volatiles.

Field work has previously shown[6] the Mount Clough pluton, throughout much of its extent at least, to be a huge sheetlike intrusive with contacts dipping moderately to the east. This is, in part, substantiated by the marked absence of pegmatites in the schist on the west side of the pluton and the nearly complete confinement of such bodies to a broad belt of schists on the east side. It is postulated that upon crystallization of such an intrusive mass the residual liquids rose to escape through the hanging wall, forming a wide zone of pegmatites in the overlying schists. The schists in the floor of the

[5] *Op. cit.*, p. 1376.

[6] Chapman, *op. cit.*, p. 163.

intrusive, on the other hand, should be nearly devoid of pegmatites, and this they appear to be.

There is a small abandoned pegmatite pit at 72° 15′ 00″ W. Long., 43° 21′ 27″ N. Lat. (Fig. 1). The pegmatite itself occurs as a tabular body 10–20 feet thick and outcrops along its strike for a distance of more than 300 feet. Its contacts are nearly concordant with the foliation and bedding of the inclosing Littleton schist, which strike N. 30° E. and dip 20°–30° southeast. Mineralogically this pegmatite is different from most of those associated with the Bethlehem gneiss in that potash feldspar is notably absent. Quartz, albite, and muscovite are the most abundant minerals. Black tourmaline, garnet, biotite, and triphyllite occur in minor quantities.

The upper contact of the pegmatite is well exposed on the south wall of the pit. Here apparently the overlying Littleton schist has been replaced by certain minerals from the pegmatite to a distance of 1 or 2 feet from the contact. This was confirmed both by megascopic and microscopic observations.

Microscopic study of the unaltered schist, a few feet from the contact, shows it to be a well-foliated, medium-grained schist. Quartz and oligoclase constitute about 65 per cent of the rock and occur in irregular or elongate grains 0.1–1.0 mm. across. Quartz is much more abundant than oligoclase. Nearly 20 per cent of the schist consists of red-brown biotite in well-oriented flakes up to 1 or 2 mm. long. Muscovite also occurs in well-oriented flakes of about the same size but is not so abundant as biotite. Garnet, sillimanite, chlorite, apatite, magnetite, and zircon occur only in minor amounts.

Thin sections of schist, collected at several places within a few inches of the contact, show numerous differences from those of the unaltered mica schist. In general the foliation of the altered schist is poorer, the grain size coarser, and the mineral composition different and more variable. One of the most outstanding differences, megascopically as well as microscopically, is the great abundance of tourmaline in the altered schist. In outcrop the tourmaline appears in tiny, black crystals up to several millimeters long arranged in streaks and layers parallel to the foliation of the schist. It is also apparent that tourmaline is more abundant close to the contact than it is farther away. Microscopic study shows abundant olive-brown

crystals of tourmaline replacing all other minerals. Some crystals are well formed, whereas others are very irregular; and many of the largest ones poikiloblastically inclose quartz, feldspar, and mica. In many instances the tourmaline distinctly cuts across flakes of biotite and muscovite. It seems certain, therefore, that large quantities of tourmaline were introduced into the schist and that tourmalinization was definitely controlled by the schistosity, because the mineral is concentrated in layers parallel to this structural feature.

It is nearly equally apparent from thin-section studies that muscovite has been introduced into the schist near the contact. Large, clear flakes of muscovite cut cleanly across crystals and grains of biotite, quartz, and feldspar. Although most of the muscovite is as well oriented in the planes of foliation as the biotite, yet it is not uncommon to find flakes of the former cutting the schistosity at large angles. Another fact in favor of the idea that muscovite has been introduced is the greater abundance of this mineral in the schist near the contact. The belief that much soda was also introduced is supported by the fact that the plagioclase of the altered rock is albite rather than oligoclase and is abundant. The albite is in anhedral grains up to 2 mm. long and shows well-developed albite twinning. There is some evidence indicating that quartz has also been introduced, but this is not so clear as in the case of tourmaline, muscovite, and albite.

It cannot be questioned that much material has been introduced into the schist of the Littleton formation from the pegmatite or by solutions genetically related to the pegmatite. The exact time of introduction, however, is a more difficult problem. Two facts indicate that the process of replacement postdated the development of a foliation in the schist. (1) Both tourmaline and muscovite have been concentrated along the schist layers. (2) The bands of biotite, which comprise nearly 20 per cent of the unaltered schist, have been so intensively attacked and replaced in the altered rock, principally by tourmaline and muscovite, that only a few per cent of the original biotite is left. In some specimens near the contact considerable muscovite, in large flakes, has been introduced at the expense of biotite. The remaining biotite retains its original orientation and partly preserves the schistosity; the muscovite, however, is younger and com-

monly cuts across the schistosity. It seems evident that replacement was accomplished at essentially the same time (possibly a little later) as the formation of the pegmatite itself. It is concluded, therefore, that the pegmatite was intruded after a foliation had been produced in the surrounding metamorphic rocks and that the pegmatite is younger than the main period of folding.

Well within the pegmatite are numerous large fragments of schist up to several feet across. The random orientation of the schistosity in these blocks testifies as to their strictly xenolithic habit. Field observation shows intense tourmalinization and muscovitization, and microscopic examination shows considerable introduced albite. So complete is this alteration that the boundaries of the fragments are, in many cases, vague and gradational. These incorporated blocks of modified schist leave little doubt that the pegmatite must have formed after the main period of metamorphism. The xenoliths cannot be detached blocks which became foliated after incorporation, because there is a great diversity in orientation of the schistosity in the various blocks.

To carry the proof a step further, many of the inclusions show a distinct crinkling of the schistosity. This crinkling is recognized in the schists throughout much of the surrounding country, and the axes of the crinkles are known to be essentially parallel to each other over wide areas. These crinkles in the foliation must have formed subsequent to the foliation itself and probably during the late stages of metamorphism when only weak stresses were active. It seems quite evident, therefore, that the pegmatite is distinctly younger than the main period of metamorphism and even younger than the crinkling.

Several pegmatites were observed which have apparently caused a slight disturbance of the intruded rock. Within an inch or so of their contacts, the foliation of the schist is crinkled; but these crinkles are local and are not to be confused with the regional crinkles considered above, so common in the surrounding schists. The strike of the axes of these local crinkles and the overturning of their axial planes are not in conformity with the regional crinkles but are in harmony with the belief that the crinkles are the result of drag along the walls of the intruding pegmatites. This drag in the folia-

tion must have occurred after the schistosity had formed, again indicating that the pegmatites are younger than the foliation.

SUMMARY

A study of the numerous pegmatites genetically related to the Bethlehem gneiss of west-central New Hampshire leads to several significant conclusions regarding the tectonics of the region. The more important of these conclusions will be summarized.

1. The great abundance of pegmatites associated with the Bethlehem gneiss indicates an original magma rich in volatiles.

2. The great abundance of pegmatites in the Littleton schist on the east side of the pluton and the lack of them on the west side is in support of the theory that the Bethlehem gneiss throughout much of its extent is a huge sheetlike intrusion with contacts dipping to the east at moderate angles. Residual liquors would escape more easily through the hanging wall of the intrusion than through the foot wall.

3. Shear-zone pegmatites in the Bethlehem gneiss indicate that the foliation of the gneiss is a primary and not a secondary structure. Shearing in a nearly crystallized mass created zones of loosely packed crystals into which was drawn pegmatitic material from adjacent portions. The drag of the biotite layers due to this deformation indicates that the foliation had formed before the mass was completely solid and is, therefore, a primary structure.

4. Filled-fissure pegmatites, apparently filling diagonal and cross joints cut cleanly across the foliation of the Bethlehem gneiss but are themselves undeformed. This fact indicates that the pegmatites formed in a rigid body after the rock had become foliated. Considering the brief time interval between solidification of the gneiss and formation of its pegmatites, the foliation must be considered a primary structure.

5. Pegmatites in the Littleton schist offer four lines of evidence that the schist-producing phase of metamorphism had been completed when the pegmatites themselves were intruded. (*a*) Replacement of schist in contact with pegmatite and of schist xenoliths within pegmatite was definitely controlled by the schistosity. (*b*) Replaced xenoliths within pegmatite still preserve crinkles which

formed on the planes of foliation before the xenoliths were engulfed. (*c*) Crinkles in the schistosity at the contacts of several pegmatites are of such a nature and orientation as to indicate that they were produced by the pegmatite during its intrusion; the pegmatite, therefore, is younger than the schistosity. (*d*) The orientation of most of the pegmatites in the Littleton schist was controlled by the schistosity. Locally they may cut across this structure, but they themselves are not sheared.

6. In so far as the pegmatites are essentially contemporaneous with (slightly later than) the intrusion of the Bethlehem gneiss, it is concluded that the gneiss is younger than the schistosity of the metamorphic rocks.

7. The pegmatites furnish some evidence as to the ages of the intrusion and the metamorphism. The fact that pegmatites, and sills of Bethlehem gneiss as well, cut the Littleton schist of Lower Devonian age[7] would indicate that the intrusion is younger than Lower Devonian. B. M. Shaub[8] has estimated the age of uraninite from one of the pegmatites in the Littleton schist to be late Devonian. The age of the nearly concurrently intruded Bethlehem gneiss should be similar. Realizing, of course, that evidence is meager, the writer, along with others who have worked in the vicinity,[9] favors the belief that the Bethlehem gneiss is of late Devonian age. Since the development of the schistosity in the surrounding rocks and the intrusion of the Bethlehem gneiss were not widely separated in time, the metamorphism probably occurred also in late Devonian time.

[7] Billings, *op. cit.*, p. 494.

[8] "The Occurrence, Crystal Habit, and Composition of the Uraninite from the Ruggles Mine, Near Grafton Center, New Hampshire," *Amer. Min.*, Vol. XXIII (1938), p. 339.

[9] Billings, *op. cit.* Fowler-Lunn and Kingsley, *op. cit.* J. B. Hadley and C. A. Chapman, "The Geology of the Mt. Cube and Mascoma Quadrangles, New Hampshire" (Concord, N.H.: State Planning and Development Commission, 1939).

AN UNUSUAL LANDSLIDE

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ABSTRACT

In a road-cut near Zanesville, Ohio, an unusual type of mass-movement occurred which was largely horizontal, producing a "pseudo-graben" at the head of the slip. This condition is of interest since only normal slipping occurred on the opposite side of the road-cut under apparently similar conditions.

INTRODUCTION

"Recognition of the importance of mass-movement in the shaping of the lands has lagged far behind our knowledge of the action of running water, glaciers, wind, and waves."[1] While mass-movements have been well classified in the excellent work of Sharpe and others, and the general conditions under which they occur have been outlined, it is the conviction of the author that much work needs to be done in recording specific sets of conditions under which these phenomena take place in order that we may understand them more fully. The following observations are, therefore, recorded as a contribution to the knowledge already accumulated concerning these important geologic phenomena.

During the summer of 1939 U.S. Highway 40 east from Zanesville, Muskingum County, Ohio, was improved and straightened. At Georgetown, in Perry Township of Muskingum County, about 9 miles east of Zanesville, a considerable area having the same general elevation above the present drainage system made a road-cut necessary. This cut was so constructed that the sides sloped 38°–40°.

Closer study disclosed the fact that the upland is underlain by deeply weathered sandstone which still retains its original structural and textural characteristics but which crumbles easily into sand. This fact, together with the upland's position above drainage, leads us to conclude that the upland may be an old erosion surface.

[1] C. F. Stewart Sharpe, *Landslides and Related Phenomena* (New York: Columbia University Press, 1938), p. 3.

DESCRIPTION OF SLIDE

During the night of April 17, 1940, a "landslide" 275 feet in length occurred on the north side of the road-cut. Throughout most of the length of the slip the whole slope up to and including a portion of the upland was affected, but toward the east and west ends the upper edge of the slipped area tapered downward until finally the break in the slope died out.

The slide possesses some of the characteristics of earthflow and associated slumping as diagramed by Sharpe,[2] but it also displays some unusual characteristics resembling step-faulting and graben structure.

The toe of the slip bulges somewhat, forming a low ridge parallel to the sides of the cut. For the most part, this ridge is composed of loose slide rock such as is found covering the unaffected slope. In one place about equidistant from the ends of the slip it is composed of weathered shale of the consistency of clay. About 2 feet above this low ridge are one or more sharp-crested ridges having a vertical or almost vertical inward-facing scarp and a gentler outward slope which is essentially part of the original slope of the cut.

About 15–20 feet above the road level is a pseudo-graben which varies from 5–8 feet in depth and from 15–18 feet in width between vertical faces. The bottom of this trough is covered with brecciated material, now badly disintegrated by weathering, broken both from the sharp-crested ridges on the roadward side and from the upland. Along the edge of the trough adjacent to the upland, blocks of the latter have dropped vertically from 3 to 6 feet or more, forming small, grassed terraces on this side of the pseudo-graben. Some of these terraces slope backward at a small angle, while others remain parallel to the surface of the upland from which they dropped.

It is interesting and significant to note that sharp ridges were formed where the slope of the cut has moved; but where portions of the upland have been affected, the pseudo-graben is also present. Near the west end of the slip, where the movement did not affect the upland, the sharp-crested ridges have been broken into spires by joints that have widened by slipping and weathering. These joints

[2] *Ibid.*, p. 54, Fig. 8.

FIG. 1.—View of the slip showing the west end tapering down toward the road level

FIG. 2.—The slip looking east from the upland level. The sharp-crested ridges may be seen to the right, the pseudo-graben in the center, and the upland on the left. Note the block broken from the upland.

FIG. 3.—Looking west along the slip. The sharp ridges may be seen below the man who is standing on one of the blocks of upland which has dropped into the pseudo-graben.

FIG. 4.—Near the west end of the slip widening of joints has broken the sharp ridges into these spires.

have partly controlled the trend of the "slip scarp," as is shown in Figure 6.

A housewife whose home is on the upland just above the slip explained, when questioned, that when she looked out in the morning there appeared to be a ditch along the top of the cut. Some time later she went to the slope and noticed that the ditch "looked like a furrow made by a big plow with the ridge toward the road." This part of the movement, she explained, went on slowly, and about 3

FIG. 5.—The earth flow which forms the toe of the slip may be seen at the left just above road level. The sharp ridges are at the center and the pseudo-graben to the right. Note the block of upland that has slipped into the pseudo-graben below the pole.

hours later portions of the upland settled vertically, the movement being more rapid than that of the slip which formed the "ditch." No rumbling or noise accompanied the movement. She stated further that the slip was still moving slowly.

The three main divisions of this particular landslide are: (1) the pseudo-graben at the head of the slipped area; (2) the sharp-crested ridges and broken material in the central portion; and (3) the low ridge of the earthflow at the toe.[3]

Since these features do not agree with those diagramed by Sharpe[4]

[3] The distinction made in this paper between earthflow and slide is that suggested by Sharpe (*ibid.*, pp. 17–18).

[4] *Ibid.*, p. 54, Fig. 8.

or with those indicated by J. K. Rogers,[5] the slide aroused the curiosity of the author and prompted further study in order to determine, if possible, the cause of its peculiarities.

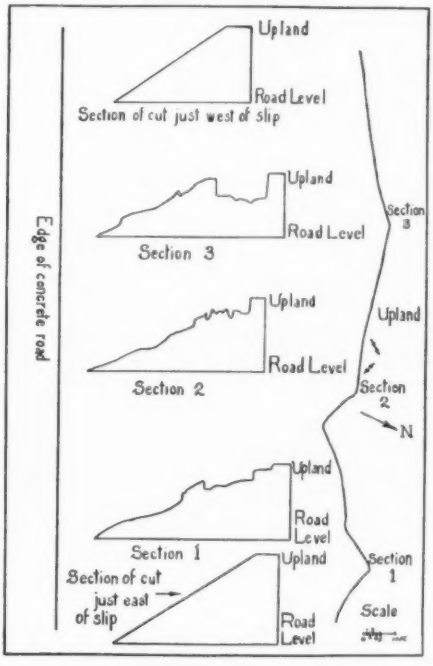

FIG. 6.—Profiles of the road-cut. At the east and west ends of the slip is the unaffected slope. The three profiles of the affected area were made at points indicated on the line at the right which shows the trend of the slip scarp. The double-headed arrows indicate the directions of strike of the joints in the rock underlying the upland.

GOVERNING CONDITIONS

It has been adequately pointed out in the literature that a number of conditions favor mass-movement. Among these the lithologic, stratigraphic, structural, topographic, climatic, and organic factors have been given prominent places.

In order to obtain lithologic and stratigraphic data the following

[5] "A Type of Landslide Common in Clay Terraces," *Proc. Ohio Acad. Sci.*, Vol. VIII (1929), p. 304.

stratigraphic section was measured in the road-cut just east of the slip and on the same side of the road.

The vertical, outward-facing scarp at the top of the cut, the down-dropped blocks of upland, and the sharp ridges were found to be composed of sandstone so weathered to a depth of 7 feet that it crumbled into sand very easily. This, in turn, is underlain by weathered and broken shale. Both the shale and sandstone are well jointed. About the level at which the earthflow occurred the red and blue clay shale is found weathered into clay on the outcrop (Table 1, No. *2*). The

TABLE 1

	Feet	Inches
7. Sand and sandy soil to top of slope	6	10
6. Weathered sandy shale, very sandy toward top	12	6
5. Clay, blue-gray	1	6
4. Thin-bedded, fine-grained, micaceous sandstone	1	0
3. Sandy shale with limonite nodules	1	0
2. Red and blue mottled clay shale	2	6
1. Blue shale, sandy near base, becoming argillaceous near top	4	1

TABLE 2

Date	Inches of Rain*	Date	Inches of Rain*
April 7	0.08	April 13	0.04
April 8	0.09	April 14	0.00
April 9	0.06	April 15	0.54
April 10	0.00	April 16	0.49
April 11	1.25	April 17	0.23
April 12	0.03		

* For 24-hour period ending midnight.

blue-gray clay (Table 1, No. 5) just below the jointed sandy shale is the horizon upon which the slide took place.

Topographically the area is a well-grassed, slightly sloping upland except for the bare slope of the road-cut. The flattest portion of the upland is just above the slope on which slipping took place.

A rain gauge operated by the Muskingum Climatic Research Center is located about 600 feet from the slip. From this station it was possible to obtain data relative to the rainfall preceeding the time of slipping. From March 13 to March 31 a total of 1.82 inches of rain fell. During this 19-day period rainfall was recorded on 11 days. From April 1 to April 17 the record shows a precipitation of 3.32 inches. Table 2 shows the distribution of rainfall for the 10-day period immediately preceding the date of slipping.

EXPLANATION OF SLIDE

The foregoing facts are significant in explaining this slide. The toe of the slide may be explained as a normal earthflow brought about by the weathering of the clay shale on the outcrop and the subsequent saturation of the flow material. However, the vertical inward faces of the ridges and the pseudo-graben cannot be explained entirely on the basis of normal earthflow and slumping, which often occur together on steepened slopes. A study of the scale diagram (Fig. 6) shows that the sharp ridges appear to have moved horizontally and not along a curved slip surface, as in normal slumping. In some places it was possible to examine the clay beneath and adjacent to the spires which are found at the west end of the slip. Here the clay, which shows no sign of disturbance, dips 3.5° toward the road. It would, therefore, appear that the material of the ridges had moved in an essentially horizontal direction.

The porous, sandy soil and deeply weathered sandstone and sandy shale permitted considerable water to enter the ground under the upland. Since the upland just above the slipped area is more nearly level than at any other place along the cut and is well covered with grass, more water could enter here than elsewhere. Thus, after protracted rains the upper surface of the clay layer would become saturated, and friction between the clay and its overburden would be reduced more here than in any other portion of the cut. Since this clay has a slight initial dip toward the road, if friction is sufficiently reduced, gravity aided by recent thawing could then cause a slip with a small downward component and a large horizontal component. The fact that this horizontal type of slip took place on the north side of the road only and that, when slipping occurred across the road on the south side, it was of the slumping type lends support to this theory.

Frequent observations have been made throughout the summer and fall following the initial movement. While rainfall conditions comparable to those shown in Table 1 have occurred several times, no further slipping has been noted; the earthflow, however, has become more pronounced. This fact would seem to indicate that thawing played an important part in initiating the movement.

As the material of the slope moved outward along the clay layer,

a tension crack developed on the edge of the upland which widened as the mass moved away from the upland, leaving a trench from 15 to 18 feet in width, which constitutes the pseudo-graben.

If the edge of the upland had collapsed, it would have fallen forward into the pseudo-graben and would have added to the brecciated material covering the floor of the trough; instead of this the edge of the upland sank as a block. This sinking may perhaps be explained by differential pressure. The weight of the upland exerts a greater pressure on the clay beneath it than is exerted on the clay in the pseudo-graben by the fallen material. If the clay is wet enough to be plastic, this pressure might squeeze some clay from under the upland laterally into the graben permitting a block of the upland to sink and thereby widen the tension crack or pseudo-graben. Thus the block sinks as it makes way for itself by forcing out the clay.

Near the west end of the slip a crack, from a fraction of an inch to 5 inches wide and in places open to a depth of 39 inches, developed 3–5 feet from the edge of the upland and nearly parallel to it. When first noted, the surface on both sides of this crack was on the same level, but several weeks later it was found that the block between the crack and the slip scarp had moved upward from 1 to 2 inches. This would seem to strengthen our conclusion that clay was moving outward from under the upland. If the clay were being squeezed toward the trench, this marginal block could thus be raised.

Samples taken with a soil auger at various depths beneath the irregular floor of the trough reveal blue-gray clay intermixed with the weathered, brecciated material of the floor. Pieces of clay were found in such position as to indicate that they had been disturbed. Such conditions would exist if the clay were squeezed from under the upland, as has been suggested.

It is significant that the slope across the road from this slip has not been disturbed in the same manner but has been affected only by ordinary earthflow and slumping. It is also significant that the whole cut on the north side of the road has not been involved in the slipping. While the factors which favor mass-movement were present on both sides of the cut, only a portion of one side yielded in the peculiar way noted. The varying effects observed must be due to varying combinations of these governing factors. It is therefore

necessary to collect a great body of information on mass-movements, giving particular attention to the combination of factors which have produced the results, if we are to understand these important geologic phenomena.

ACKNOWLEDGMENTS.—The writer gratefully acknowledges his indebtedness to his colleague, C. F. Moses, for suggestions and criticisms and for photographs used in the article. To Dr. G. W. Conrey, of Ohio State University, for criticism of the manuscript and suggestions the author is deeply grateful. Credit is also due to Harry Rankin, a student, for his assistance in the preparation of the scale diagram, as well as for photographs.

ACID CLAY—AN AGENT IN CHEMICAL WEATHERING[1]

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ABSTRACT

A generalized consideration of the nature, importance, and distribution of the acid clays was made. The physical-chemical nature of the acid clay was compared with some of the more familiar ordinary acids.

A study of the effect of the acid clay in chemical weathering by mixing primary minerals with suspensions of acid clays revealed that the acid clay was extremely effective as an agent in weathering. In a comparatively short time interval of 107 days 3.4 per cent of the crystal-lattice calcium of anorthite was transferred from the mineral crystals to the adsorbed atmosphere of the clay. The hydrogen adsorbed on the clay was effective in bringing about removal of calcium from crystals of hornblende and augite. Reactions with biotite and microcline were found to be extremely slow.

The importance of the acid clay and its place in natural weathering, giving consideration to equilibrium conditions, completeness of reactions, etc., are discussed.

INTRODUCTION

The weathering of rocks and minerals has been understood in a general way for a long time, but most of the detailed steps of the chemical processes and mineral change are not yet thoroughly worked out. The problems of chemical weathering have lain in a "no man's land" between the one field of restricted geology and the other of refined chemistry without receiving concentrated attack from the scientists of either field; but soil scientists investigating the origin of their soils are moving into this uncharted area and, by using a combined chemical technique and mineralogical knowledge adapted specially to a study of the chemical breakdown of rocks and minerals, are making discoveries equally as interesting and helpful to geologists as to pedologists.

Formation of the various clay minerals (kaolinization) unquestionably hinges largely upon the hydrolysis of alumino-silicate minerals. S. Goldich[2] concludes that the union of water and rock minerals can be considered the most important process of decomposi-

[1] Contribution from the department of soils, Missouri Agricultural Experiment Station, Columbia, Mo. Journal Series No. 697.

[2] "A Study in Rock Weathering," *Jour. Geol.*, Vol. XLVI (1938), pp. 17–23.

tion. Thus the hydrolysis which involves the decomposition of both water and the mineral becomes so important that a full understanding of this process cannot be minimized. The ubiquitous chemical agent, water, acting through abundant geologic time, actually develops compounds (acid clays) with primary silicates which act as further agents of weathering.

Reviewing the mechanism of hydrolysis, water reacts with many substances (salts) to produce two new substances, one of which contains hydrogen and the other the hydroxyl, both derived from the water. One of these reactions demonstrated in the laboratory because of its rapidity of completion is

$$FeCl_3 + 3HOH = Fe(OH)_3 + 3HCl\,.$$

Another, which goes on slowly, requiring years for completion, is

$$KAlSi_3O_8 + HOH = \underset{\substack{\text{(Hydrous}\\ \text{alumino-}\\ \text{silicate)}}}{HAlSi_3O_8} + KOH\,.$$

In the above equations water acts as a weak acid, ionized to give H ions, and is the acid reagent which brings about the chemical reactions. Water, because of its OH ions, can likewise react as a weak base with other salts, but this effect is not ordinarily operative in weathering processes. The action of common acids on other compounds is the same as the action of water, with the hydroxyl (OH) or anion of the acid water being contained in the new substance formed just as the anion of any other acid is contained in one of the new substances formed.

Physical chemists have found that the dissociation of the hydrogen from pure water gives a concentration of hydrogen ions such that 1 liter of pure water contains 0.0000001 gm. of ionized hydrogen, or the hydrogen which acts as an acid. If this water comes to equilibrium with the carbon dioxide of the soil atmosphere (the condition existing in nature), the hydrogen-ion concentration is increased to 0.000001 gm. per liter, or ten times that in the pure water. Hence, typical ground water is a far more powerful weathering acid than pure water.

A. Demolon[3] reports that pure water will dissolve in 8 days the following amounts of K_2O from 2 gm. of pulverized rock: when such is granite, 0.54 mg.; altered granite, 1.32 mg.; gneiss, 0.31 mg.; and syenite, 0.62 mg. Water which contains CO_2 will remove from the same rock approximately ten times as much soluble K_2O, or the following amounts: granite, 6.24 mg.; altered granite, 7.64 mg.; gneiss, 7.72 mg.; and syenite, 6.24 mg. Such results are to be expected when we recall that the water containing the CO_2 contains ten times as much ionized hydrogen or acid as pure water. The effect of even weak acids in weathering becomes very apparent.

Now the acids recognized as active in geologic processes are water ($H^+ OH^-$), the slightly stronger carbonic acid (H_2CO_3), and the complex organic acids produced by the decomposition of plant residues. Another group of acids hitherto unrecognized as agents in weathering, but which contain large amounts of hydrogen and which can affect primary mineral weathering greatly, have been recognized in the unconsolidated soil covering of most regions. They are the colloidal clay acids commonly associated with the colloidal clay complex. It is their significance as agents in mineral decomposition that needs recognition and fuller appreciation. These colloidal acids occur in geologic materials of humid and semihumid regions. It was because of their abundance and rather common occurrence that it seemed desirable to determine experimentally what effect such clay acids have as hydrolytic transformers of primary minerals.

THE NATURE OF THE CLAY ACID

That the colloidal clay acid, i.e., the alumino-silicate complex with H^+ ions, is very similar to an ordinary weak acid, such as acetic acid, has been demonstrated by physical-chemical measurements. In each case there is a large amount of total hydrogen available for reaction with a base, but only a small amount of dissociated or ionized hydrogen. A very large percentage of the hydrogen ions of the colloidal system are in close proximity to the colloidal particle, serving as reserve acidity which would be available for reaction with a base such as NaOH, but do not affect a pH measurement of the suspension. A relatively small number of truly ionized hydrogen

[3] *La Dymanique du sol* (Paris: Dunod, 1932), p. 12.

ions, or hydrogen ions at a considerable distance from the particle of clay, accounts for the nearly neutral (pH) conditions of colloidal systems which, nevertheless, would neutralize surprising quantities of base. A suspension of acid clay can be titrated against a weak base such as $Ca(OH)_2$, producing a curve which is very similar to a titration curve for acetic acid against a weak base. Figure 1 shows a titration curve for a hydrogen clay by means of calcium hydroxide.

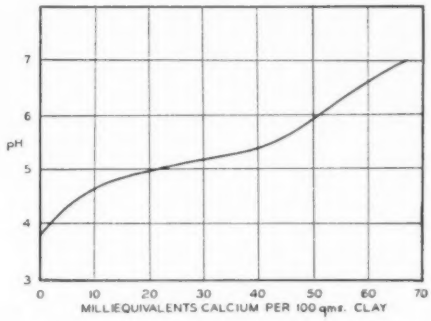

FIG. 1.—Titration curve of hydrogen clay and calcium hydroxide

The initial pH of the acid clay is not exceedingly low; yet, because of its buffering capacity, large amounts of base can be added to the system without changing the pH. In most systems the end-point must be determined electrometrically. The reaction between an acid clay and calcium hydroxide might be written as follows:

$$\begin{matrix}\text{Clay} \\ \text{Micelle}\end{matrix}\begin{matrix}-\ H^+ \\ \\ -\ H^+\end{matrix} + Ca(OH)_2 \rightarrow \begin{matrix}\text{Clay} \\ \text{Micelle}\end{matrix}\begin{matrix}- \\ \\ -\end{matrix} Ca^{++} + 2H_2O\,.$$

For many years investigators of soils have been aware of the fact that colloidal clay acids occur in both upland and bottom soils of humid regions. It has been observed, in some instances, in the state of Mississippi that the clay acids may be found even to a depth of 10 or 15 feet. After or during the formation of clay by the very slow hydrolysis of some of the primary minerals while they were weathering physically, a rearrangement of atoms occurs which re-

sults in material becoming so very finely divided as to develop an absorbed atmosphere of cations. These adsorbed cations vary greatly from one geographic climatic region to another. In the humid regions in many instances more than 50 per cent of the adsorbed ions are hydrogen, while the others are primarily calcium, magnesium, and potassium. Material which contains a large number of hydrogen ions and has a high buffer capacity or reserve acidity is said to be "unsaturated." If all the adsorbed ionic atmosphere of the clay is filled with such cations as calcium, magnesium, and potassium, the material would be referred to as "saturated" and would be neutral or basic in reaction. When part of the adsorbed atmosphere is made up of hydrogen, this condition gives rise to our commonly called "acid soils" and is remedied by the application of limestone or calcium carbonate. The chemical reaction occurring as a result of such treatment may be illustrated as follows:

$$\begin{matrix}\text{Clay Micelle} \\ \begin{matrix}-\ H^+ \\ -\ H^+\end{matrix}\end{matrix} + CaCO_3 \rightarrow \begin{matrix}\text{Clay Micelle} \\ \begin{matrix}- \\ -\end{matrix}\end{matrix} \quad \begin{matrix}Ca^{++} + H_2CO_3 \\ \qquad\quad \downarrow \\ \qquad\quad H_2O + CO_2 .\end{matrix}$$

The Putnam silt loam of Missouri, for example, has become so acid, or so unsaturated, that 100 gm. of this soil contain 15 M.E.[4] of adsorbed hydrogen, or the same amount of hydrogen that would be ionized in 150,000 liters of pure water or 150 cc. of 0.1 N hydrochloric acid. Since the surface clays in humid regions contain large amounts of adsorbed hydrogen, they are, in reality, acids and must be very effective agents in hydrolytic weathering. It was because of the fact that the adsorbed hydrogen on the clay might act as an agent in weathering that the following experimental investigation was undertaken to determine quanitatively how effective it would be on some common rock-forming minerals. The investigation consisted of treating pulverized rock minerals with suspensions of standardized clay acids extracted from soil and of measuring the shifts of ions from the minerals into the adsorbed atmosphere of the clay.

[4] Milligram equivalents will be abbreviated as "M.E." in the following pages. One M.E. is, of course, 1/1,000 of 1 H, $\frac{1}{2}$ O, $\frac{1}{3}$ Al atomic weights.

EXPERIMENTAL PROCEDURE

Crystal-pure samples of quartz, augite, microcline, biotite, anorthite, and hornblende were each ground in a ball mill until they reached a fine state of subdivision. Each sample was then placed into a liter cylinder; distilled water was added; and the fraction of silt size ranging from 0.05 to 0.005 mm. equivalent diameter was separated by means of the beaker method of mechanical analysis. This silt fraction so obtained was then placed in a Gooch crucible, and 1 liter of 0.001 N hydrochloric acid was allowed to leach slowly through it for the purpose of removing easily extractable cations. The sample was then washed free of chlorides. The pH, which was 5.8, of the aqueous solution of the leached mineral was used as the index to insure that all the basic cations released by grinding had been removed. After the mineral samples were washed free of chlorides and oven-dried, they were reserved for "weathering" treatment by the clay acid.

Colloidal clay was extracted from the heavy subsoil layer of Putnam silt loam and electrodialyzed[5] according to the method of R. Bradfield.[6] The clay suspension thus prepared contained 3.99 per cent of dry material and had a pH of 3.30. A conductometric determination of the adsorptive capacity according to the carbonation method of Bradfield and W. H. Allison[7] showed this to be 68 M.E. 100 gm. of clay. In other words, 100 gm. of the clay of the Putnam silt loam has a possible acidity of 68 M.E.

A hydrogen-clay suspension containing 5 gm. of clay was added to 10 gm. of each of the silt-size samples of the primary minerals previously prepared. By this means the pure, unweathered mineral crystal was put into contact with the weathering reagent or acid clay. The mixtures were shaken thoroughly and allowed to stand for 31 days, when the pH of each mixture was determined. This

[5] An electrical treatment which removes all basic cations from the clays and substitutes hydrogen for them.

[6] "The Chemical Nature of Colloidal Clay," *Mo. Agric. Exper. Stat. Rev. Bull. 60* (1923).

[7] "Criteria of Base Saturation of Soils," *Trans. Second Comm. and Alkali Subcomm. Internat. Soc. Soil Sci., A* (1933), pp. 63–79.

measure was repeated after 70 days and then again at the end of 107 days.

After the time interval of 107 days the weathered, adsorbed cations were made available for analysis by replacement by neutral ammonium acetate. A standard soil-analysis technique of centrifuging and siphoning of the clear supernatant liquid was employed. The ammonium acetate washing was repeated four times to insure the removal of all the adsorbed cations. The supernatant liquid was analyzed by standard quantitative procedures for its content of soluble sesquioxides, calcium, and other materials. The small amounts of silicon made soluble were removed by dehydration and filtration. The materials in solution had been freed, of course, by the action of the clay acid on the rock minerals.

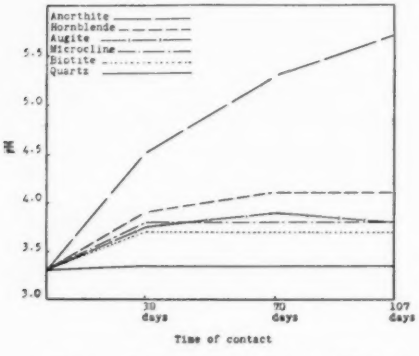

FIG. 2.—Changes with time in the pH of mineral-colloidal clay mixtures.

Another set of tests for controls was run by taking samples of three of the primary minerals—augite, hornblende, and anorthite—in the same quantities as used in the foregoing treatments and mixing with the same amount of ordinary distilled water as that contained in the suspension. After these aqueous mineral mixtures had stood for 70 days, they were analyzed for iron and calcium. This part of the experiment served to test the mineral breakdown in the presence of water at equilibrium with carbon dioxide of the air.

EXPERIMENTAL RESULTS

As a result of the hydrolysis of the primary minerals there was a decided increase in the pH of the mineral-colloidal clay mixture, indicating ready weathering in some instances and an insignificant pH change in others, indicating relative stability. This is evident in Figure 2. The pH of the anorthite-clay mixture showed the great-

est change as it shifted from 3.30 to 5.70 (from acid to basic condition as the first equation of hydrolysis shows) during 107 days.

The results of the calcium analysis presented in Table 1 show that calcium which became soluble in the mixture of anorthite and acid clay represented 3.4 per cent of the total calcium present in the

TABLE 1

ADSORBED CALCIUM AND OTHER SOLUBLE MATERIALS IN MIXTURES OF CLAY WITH MINERALS AFTER 107 DAYS

Mixture	Calcium (Mg.)	Soluble Materials Other than Calcium (Mg.)
Quartz	1.3	Trace
Augite	7.1	Trace
Microcline	5.1	Trace
Biotite	2.8	Trace
Hornblende	10.3	14.5
Anorthite	48.1	7.5

TABLE 2

IRON AND CALCIUM IN THE FILTRATE OF AQUEOUS MINERAL MIXTURES AFTER 70 DAYS

Mixture	Calcium (Mg.)	Iron (Mg.)
Augite	0.0	1.9
Hornblende	3.0	0.0
Anorthite	0.5	0.0

10 gm. of crystal sample taken at the outset—a significant amount of weathering by acid clay in 107 days. Four of the samples contained only traces of soluble materials other than calcium. The anorthite and hornblende mixtures contained significant amounts of these groups.

In the water-mineral mixtures very little soluble material was released in the same time interval as compared to the clay-mineral mixtures, according to the data in Table 2.

DISCUSSION

The results obtained in this study demonstrate the hydrolytic action by the adsorbed hydrogen of the colloidal clay on the calcium feldspar, anorthite. In this reaction the adsorbed hydrogen replaces the calcium of the anorthite, and the replaced calcium becomes part of the adsorbed ionic atmosphere of the colloidal clay. The reaction might be represented diagrammatically as follows:

$$CaAl_2Si_2O_8 + \left[\begin{array}{c}\text{Clay}\\ \text{Micelle}\end{array}\right]\begin{array}{l}-\ H^+\\ -\ H^+\end{array} \rightarrow H_2Al_2Si_2O_8 + \left[\begin{array}{c}\text{Clay}\\ \text{Micelle}\end{array}\right]\begin{array}{l}-\\ -\end{array} Ca^{++}.$$

The rate of reaction is surprisingly rapid—so rapid, in fact, that after 107 days more than 50 per cent of the adsorbed hydrogen on the colloidal clay had been replaced by calcium and 3.4 per cent of the calcium removed from anorthite of silt-size particles. The rate showed evidence of a decline as more and more of the adsorbed hydrogen was replaced by calcium. Probably the reaction would come to an equilibrium before all the adsorbed hydrogen had been replaced. In the case of a sedimentary deposit in nature, the calcium which had been replaced from the feldspar and adsorbed on the clay might be leached from the adsorbed atmosphere of the clay by percolating water saturated by carbon dioxide. Under such circumstances, where the adsorbed calcium was being removed by leaching, we might expect a certain amount of adsorbed hydrogen always to be present. As long, therefore, as leaching is occurring, the reaction between acid clays and primary minerals would continue to move basic materials out of the crystal into the clay and from the clay into the percolating waters. Since the reaction will not come to equilibrium in humid regions, it is impossible for it to continue until all the sedimentary materials become hydrous aluminum silicates mixed with the nonhydrolizable quartz.

The data show that the reaction of the clay acid on the calcium feldspar anorthite was rather rapid and complete, whereas that on microcline was barely measurable in the time interval used. This checks with observations that basic igneous rocks weather much faster than the acidic rocks. The fact that anorthite, the calcium

feldspar, was hydrolyzed much more readily than microcline suggests that the molecular arrangements of the two feldspars must be very different. W. L. Bragg[8] states that the two are nonisomorphous crystal systems, a fact which probably accounts for the ease of the calcium hydrolysis compared to that of the potassium.

The method used in this experiment has many possibilities for future study. Soil- or mineral-weathering, mechanisms of exchange cations, conditions and time intervals significant in hydrolysis, and numerous other activities could be studied by this method and from this point of view. Further similar chemical studies can doubtless give some accurate measurements of changes in mineral structure and weathering rates.

CONCLUSIONS

The study of the influence of hydrogen clay on the hydrolysis of primary minerals revealed the following:

In the comparatively short time interval of 107 days, calcium can be transposed from the crystal of anorthite to the adsorbed atmosphere of the colloidal clay in quantities as large as 3.4 per cent of the total calcium in the anorthite.

The hydrogen adsorbed on the clay can be effective in bringing about calcium removal also from crystals of hornblende and augite.

Biotite and microcline are little affected in such a short time by the action of the hydrogen adsorbed on the clay.

The hydrogen clay thus becomes a very active agent in mineral and rock-weathering processes when it causes the removal of approximately one-hundred times as much calcium from anorthite as does the hydrolytic action of ordinary water in equilibrium with carbon dioxide at atmospheric pressure. To the acids previously recognized as agents in chemical weathering we must add the colloidal acid clay.

[8] *Atomic Structure of Minerals* (Ithaca, N.Y.: Cornell University Press, 1937).

PARALLEL GULLIES ON THE SLOPES OF LASSEN PEAK

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ABSTRACT

Flood waters released by the 1915 eruptions of Lassen Peak carried a heavy load of boulders and forest debris, which was deposited on a relatively flat portion of the mountain slope. Succeeding waters were split by the boulders and caused parallel gullies to be eroded.

INTRODUCTION

Parallel gullies are not uncommon features on many types of terrain. They are found most commonly in semiarid regions where torrential rains occur, or when open joints or bedding planes direct the water in definite channels. This type of gully is also found in agricultural areas where plow or harrow furrows are placed parallel to the slope of a hill, thus converging the runoff in parallel channels. Parallel gullying as a result of volcanic activity must be of much less common occurrence.

DESCRIPTION OF GULLIES

Such a feature is found in Lassen Volcanic National Park west of the Lassen Peak Highway 9 miles from the northwest entrance to the park, where seventy-two gullies form a remarkable group on the lower eastern slopes of Lassen Peak (Fig. 1). These gullies are parallel and trend northeast. They vary in length from 20 to 600 feet, in width from 3 to 30 feet, and in depth from 1 to 18 feet (Fig. 2). Many of the gullies bifurcate along their courses, and others merge near the bottom of the slopes (Figs. 1 and 2).

These gullies were formed during the short period of May 19–22, 1915, inclusive, as a result of the activity of Lassen Peak. On the former date a mass of highly viscous dacite rose in the crater of the volcano and overflowed the western and eastern sides of the mountain. The lava on the east side of the mountain descended about 150

feet. This lava, with its accompanying heated gases, melted a part of the heavy snow pack, thus causing a destructive flood (Fig. 3). The flood, confined largely to natural drainage channels, tore out the

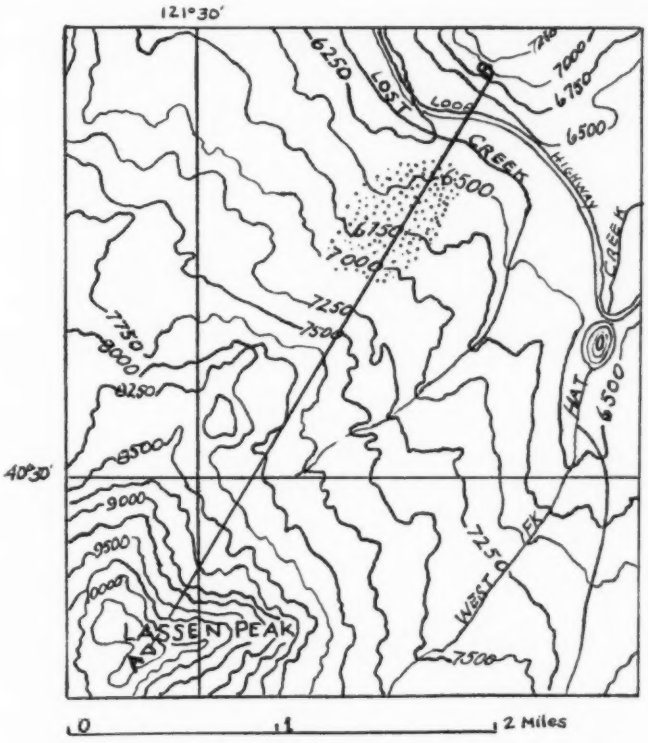

FIG. 1.—Sketch map of the area in which the gullies are found. Dotted area shows location of gullies. Line *A–B* is locus of the profile in Fig. 4.

forests on the lower slopes of Lassen Peak for a width of about 500 yards. Much timber was also destroyed along the upper courses of Hat Creek and Lost Creek (Fig. 1). The flood plain of Lost Creek was strewn with rocks and tree fragments for a distance of 18 miles along its course. The debris along Hat Creek was somewhat less. But the effect of this flood in producing gullies was probably not so great as

FIG. 2.—Gullies on the lower slopes of Lassen Peak. Flood plain of Lost Creek in foreground. (Henry C. Lind photo.)

FIG. 3.—The path of the mud flow of May 19, 1915. Note the tongue of lava near the top of Lassen Peak. Gullies were formed on slope in right center. (Loomis photo.)

that of the flood which followed. Boulders and forest debris may have been deposited in the gullied area, but the evidence is not conclusive.

ACTIVITY OF LASSEN PEAK

At about 4:30 P.M. on May 22, 1915, a blast of gas, *nueé ardente*,[1] rushed down the eastern slopes of Lassen Peak with sufficient strength to uproot or fell practically all the trees over an area of about 3 square miles. The felled trees lie with their trunks parallel and their tops pointing in the direction of movement of the blast.

The path of the blast over the first 3 miles of its course was nearly the same as that followed by the mud flow 3 days previously, but the course of the blast was several times wider and the destruction much greater. The combined result of the mud flow and blast was the feature known as the "Devastated Area," where practically all vegetation was obliterated. Accompanying the downward blast was a tremendous vertical eruption nearly 5 miles in height. Boulders and rock fragments of varying sizes were strewn over the slopes of Lassen Peak.

A study of the photographs taken at this time[2] shows that the gullies were formed at about the same time as the eruption of May 22, 1915. Little or none of the mud flow of May 19 is shown to have affected the area in which the gullies are found (Fig. 3).

The gases emitted by the May 22 eruption, which rolled down the slopes of Lassen Peak, were sufficiently heated to scorch trees along their path. There was enough heat, then, to melt that part of the snow along its path which had been left by the earlier mud flow. The snow pack has an average depth of 25 feet at an elevation of 8,000 feet; consequently, the water, suddenly released, produced a sheet flood along parts of the mountain's slopes. This flood picked up a heavy load of debris similar to that carried by the mud flow of May 19. When the waters reached the relatively flat portion of the slope

[1] R. H. Finch, "On the Mechanics of *Nueés ardentes*," *Jour. Geol.*, Vol. XLIII (1935), pp. 545–50.

[2] B. F. Loomis, *A Pictorial History of the Lassen Volcano* (Anderson, Calif.: Anderson Valley News Press, 1926), p. 135. Also photographs in the Loomis Memorial Museum, Lassen Volcanic National Park, and personal communication, Mrs. B. F. Loomis.

shown in Figure 4, the heavier fragments were dropped. Succeeding flood waters of diminished carrying power were split by the deposits,

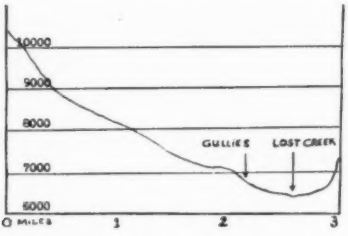

FIG. 4.—Profile of Lassen Peak through gullied area and across Lost Creek

FIG. 5.—Rock at head of a gully. A similar gully is on the other side of the rock

and gullies were consequently formed on both sides of each large protruding boulder. In some cases, tree fragments or a number of small boulders produced the same effect as a single large rock.

SUBSEQUENT HISTORY

There has been little erosion of the gullies since their formation in 1915. The rainy season in this locality is from November to May, and at the altitude of the gullies—about 7,000 feet—most of the precipitation is in the form of snow. Slope wash has filled the original V-shaped bottoms, and the divides are rounded. The boulders and tree fragments at the beginning of nearly all the gullies are still in place. Vegetation, after 25 years, is starting to renew itself to such a degree that the shallower gullies will soon be obscured (Fig. 5).

ACKNOWLEDGMENTS.—Acknowledgment is made to Professor Charles A. Anderson, of the University of California at Berkeley, for helpful suggestions and criticisms.

GEOPHYSICAL STUDY OF THE DOUGLAS FAULT PINE COUNTY, MINNESOTA

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ABSTRACT

A gravity-meter traverse across the Douglas fault in Pine County, Minnesota, has been run. Assuming the fault to be sandstone against basalt, the throw of the fault has been shown to be about 11,000 feet.

INTRODUCTION

From scattered outcrops and well-log data gathered by members of the Minnesota Geologic Survey the approximate location of the Douglas fault in Minnesota has been known for some time. This fault extends from Rush City, Minnesota, to beyond Amnicon Falls, Wisconsin. Tilted lava flows of basalt covered by sediments were faulted with the upthrow side toward the east, and after peneplanation the structure was covered by glacial drift. A map of the region near Pine City, Minnesota, is shown in Figure 1. The geologic section in this region is shown in Figure 2. In northern Wisconsin the fault is exposed in many places. From stratigraphic evidence the throw of the fault in the vicinity of Superior, Wisconsin, has been estimated by F. T. Thwaites[2] to be from 6 to 12 miles. In central Minnesota, due to lack of exposures, the nature of the fault is not so well known.

MAGNETIC SURVEY

Working on the contrast in magnetic properties of the flows and the sediments M. G. Frey[3] located the fault plane more accurately and extended its known position southward. The magnetic response along the line indicated by Frey as traverse line No. 1 south is shown in Figure 3. This line is in Sections 9, 10, and 11, R. 21, T. 38,

[1] Present address, Bureau of Ordnance, Navy Department, Washington, D.C.

[2] *Wis. Geol. and Nat. Hist. Survey Bull. 25*, p. 89.

[3] "Geology of the Region about the West End of Lake Superior." Unpublished Doctor's thesis, Department of Geology, University of Minnesota, 1939.

FIG. 1.—Map of region near Pine City, Minnesota, showing location of fault and traverse line. Wells shown by numbered circles indicate an average thickness of drift of about 125 feet.

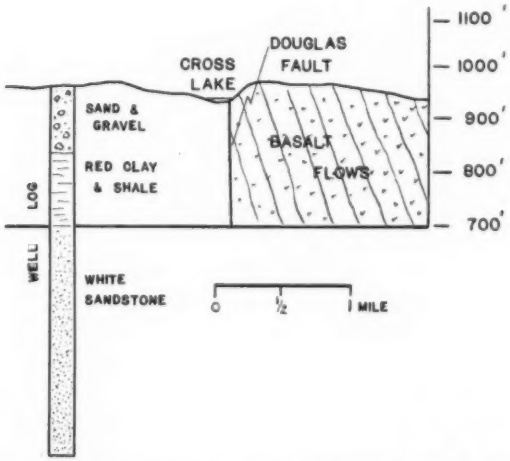

FIG. 2.—(After Hall.) Geologic profile in vicinity of Pine City, Minnesota

a few miles south of Pine City. Several difficulties were encountered in the interpretation of the magnetic data: (1) the basalt was not magnetically uniform but consisted of many successive flows with a concentration of magnetite at the bottoms of the flows; (2) successive flows did not give the same magnetic reaction, presumably indicating a difference of magnetite concentration or thickness of successive flows; (3) the dipping flows obscured the reaction of the fault face; (4) the unknown magnitude and direction of possible remnant magnetization made interpretation difficult.

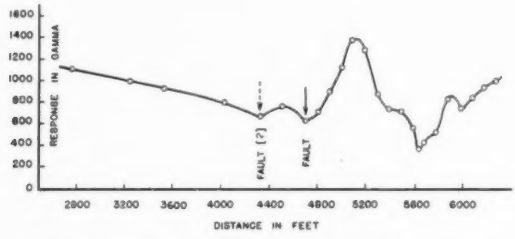

FIG. 3.—(After Frey.) Vertical magnetic anomaly of Douglas fault along traverse line shown in Fig. 2. Arbitrary zero taken at intersection of traverse line and railroad.

From Figure 3 it is seen that the alternate layers of basalt of high and of low magnetite content cause a very irregular magnetic response over the upthrow side. Since this irregularity is absent over the downthrow side, Frey has been able to show that the throw of the fault near Pine City is in excess of 2,000 feet.

GRAVITY-METER SURVEY

Because the flows are more uniform in density than in magnetic susceptibility, it was thought that the location of the fault plane, its dip, and the throw of the fault could be determined more accurately by means of a gravity-meter survey. A traverse was run over the same line for which the magnetic data are given. Samples of the basalt and of the sandstone for density determinations were furnished by Dr. Frank F. Grout, who also furnished information relative to the percentages of oxidized and unoxidized basalt in the

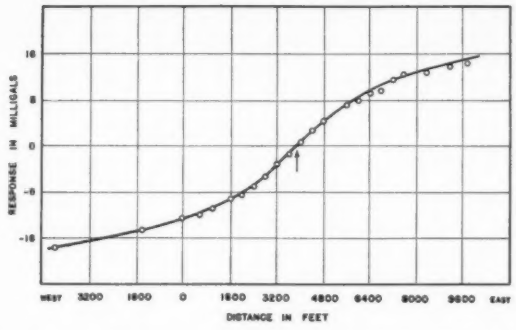

FIG. 4.—Gravitational anomaly of Douglas fault along traverse line shown in Fig. 2. Circles indicate observed values. Curves show theoretical values calculated from configuration shown in Fig. 5. Arrow indicates position of fault.

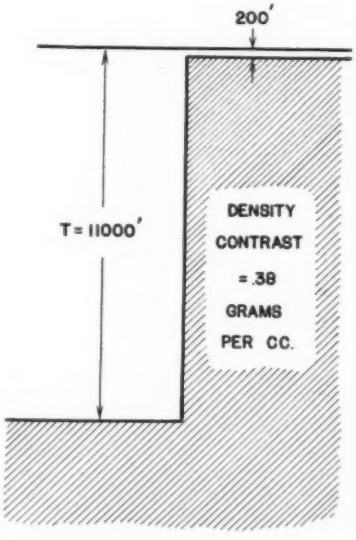

FIG. 5.—Geometrical configuration used to calculate data for theoretical curve shown in Fig. 4.

flows. Measurements with a Joly balance gave a density contrast between sandstone and basalt of 0.39 grams per cubic centimeter.

In Figure 4 the plotted circles are the observed values of gravity difference measured from a zero value at the fault plane, and the curve drawn is the theoretical response due to a fault having the cross section shown in Figure 5. Bouguer, free-air, and normal corrections have been made to these data. The probable error is about 0.2 milligal. The high degree of symmetry about the point 3,900 feet indicates that the fault plane is very nearly vertical.

The agreement of the field data with the theoretical curve is seen to be very close. By drawing various curves for different geometrical

TABLE 1

T (Feet)	Density Contrast in Grams per Cc.
8,000	0.47
9,000	.44
10,000	.41
11,000	.38
12,000	.36
13,000	0.34

arrangements and for different density contrasts it is possible to show that, if one assumes the fault to be sandstone against basalt, the throw is about 11,000 feet, and it is highly improbable that it is less than 9,000 feet or more than 13,000 feet.

In the method of interpretation employed, the throw of the fault was determined from the shape of the curve and from this the density contrast was calculated through the Bouguer relationship. Assuming the following values of T (Fig. 5), matching the theoretical curves to the field data as closely as possible yields Table 1. The value of density contrast of 0.38 grams per cubic centimeter corresponding to a value of T = 11,000 feet, for which the curve matching is the best, is in close agreement with the value of 0.39 grams per cubic centimeter determined by laboratory density measurements.

CONCLUSIONS

The Douglas fault has been shown to be nearly vertical. Assuming the fault to be sandstone against basalt, comparison of the field curve

with standard curves shows that it is highly improbable that the throw is less than 9,000 feet or more than 13,000 feet. The most probable value of 11,000 feet for the throw yields a density contrast between the basalt and sandstone which is in very close agreement with the value obtained by density measurements in the laboratory.

ACKNOWLEDGMENTS.—The author is very much indebted to Dr. W. W. Wetzel of the department of physics of the University of Minnesota for his helpful suggestions during this research. The co-operation of the Minnesota Geologic Survey in financing the field work is much appreciated.

NATIONAL INTROSPECTION IN GEOLOGY

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This theme, which has troubled the writer for many years, has been suggested again by a criticism contained in a review by A. C. Tester of *Recent Marine Sediments* by Parker D. Trask *et al.* He states: "The contributions of Europeans and Americans usually contain many more references to articles published in their own continent, even though the subject has been studied in both continents."[1] It is just a little amusing to notice, even in this criticism itself, that there appear to be two continents only.

We who live in "the little countries" (apparently too insignificant to be thought of in this connection) are painfully aware of the tendency referred to. The present note is not to be interpreted as a criticism of our European and American colleagues, to whom we are deeply indebted and profoundly grateful for assistance, direct and indirect. It is rather a plea for still greater help in the future than in the past.

It is an old proverb that "the onlooker sees most of the game." It is certainly true that we geologists in the little countries farther away from the vortices of scientific thought are compelled by our very isolation to seek guidance from our more favorably situated confreres in "the two continents." In this way we obtain, possibly, a rather better-balanced picture than do those who are surrounded by a plethora of riches.

The fault, if it be a fault, forming the subject of this note is really a penalty of greatness. In the "big," rich, closely settled countries around the North Atlantic Basin, possessing large and dense populations with a high concentration of scientific workers, there are greater opportunities for scientific research and particularly for bibliographic studies in connection therewith. We in the "other places" are few, scattered, and largely preoccupied with "bread and butter"

[1] *Jour. Geol.*, Vol. XLVIII (1940), p. 328.

problems. Our opportunities for mutual discussion are few, and our media of expression through publication are limited. Naturally, papers by us on purely local aspects of our subject, published locally, never reach workers in the two continents. Unfortunately for us, the same fate attends our more serious contributions to general geological philosophy.

In the big countries opportunities for meeting and discussion abound on every hand and all the time. The enormous volume of scientific literature, becoming ever more and more specialized, is no longer a spate or torrent but a veritable sea-flood. Even those in the favored environment have difficulty in keeping their heads above water. They have neither time, opportunity, nor necessity to look around to see what may be drifting about in the flood outside their own immediate proximity.

In Europe, where countries are smaller and populations are highly concentrated, geologists are being forced more and more into studies of great detail—once irreverently referred to by an English friend as "cesspit geology." In such concentrated studies local sources of information are naturally of prime importance, and there is no need to go outside purely parochial literature.

Americans are more fortunate in many respects. While possessing all the advantages associated with an enormous and wealthy population with innumerable centers of learning and specialized culture, the country provides ample "elbow room." Broad outlines are already clearly and permanently drawn in firm lines and not simply dotted in as hazy sketches as in less favored lands. Yet there still remain, in most areas, all the major details of shading to be inserted to complete the picture. The geologist has not to waste his energies in time-consuming empirical traverses to determine where he has to start. In most instances he has ready access by regular public conveyance to any locality in which he decides to carry out his research. He has not the necessity for making long cross-country motor journeys carrying his own fuel and supplies or of traveling for weeks at a stretch on camel back or with pack horses through areas which are still geologically a terra incognita.

A completely ample and satisfying literature in his own language is available to him at his own academic or institutional center. Small

wonder then that he feels neither the urge nor the necessity to delve into literature from other countries, even though the "curse of Babel" may not enter into the consideration. There are few van der Grachts able to express themselves with equal facility and elegance in any one of half-a-dozen languages at will.

We who view the scene from afar realize with envy that national introspection does not indicate any slothful desire to follow the path of least resistance. The worker has all that heart could wish and is not forced by poverty and starvation to appreciate that there are other supplies of mental pabulum available. He does not have to hunt for his living but has it delivered at his door in neatly arranged parcels.

Nevertheless, we outsiders sometimes feel with Tester that it would be to the mutual advantage of all concerned were there a more extensive exchange of views. The writer has been impressed for years by the fact that, rich as is the treasure-house of North American geology, there are some exotic products not there represented which could add spice and flavor to the already rich dishes served up in the favored environment, were a little search made for them. North America does not illustrate every phase of nature's moods and methods.

The following example of what may be termed the "North Atlantic complex" is mentioned because its very triviality, while illustrating a general though obviously unconscious tendency, cannot by any stretch of imagination be construed into adverse criticism. Surely no modern work on a geological subject can have surpassed Twenhofel's treatise on sedimentation in the thoroughness and balance with which literature, domestic and foreign, has been combed for material. If any work can be absolved from the charge of parochialism, it is this all-embracing treatise. Yet, in describing the work of burrowing animals (p. 104), the census includes "crayfish, muskrats, beavers, moles, prairie dogs, gophers, skunks, ants, and earthworms." The list does very well as far as North America is concerned. But few of the animals mentioned exist in certain other continents, and the barest mention is made of those characteristic of other lands. In the list there do not appear the names of even the widely distributed rabbit and fox. One could scarcely expect notice

to be taken of antipodal animals like the numerous burrowing marsupials, birds, lizards, and wasps of so insignificant a country as Australia; though the actual tonnage of soil and subsoil turned over by them is probably at least comparable with that moved by their American prototypes. Surely, however, the animal responsible in all probability for a quantitative effect equal to all the rest combined namely the termite, might have received passing mention.

In Australia we are hampered by enormous distances and limited transport. Perth in Western Australia is 2,500 miles from Sydney in New South Wales. The nearest point of our sister-dominion, New Zealand, is 1,200 miles in the opposite direction. Our Australian centers of population are concentrated within a few areas separated by vast empty spaces. Imagine having the population of the United States reduced to seven millions and having about 95 per cent of this population concentrated to the northeast of a line joining Charleston and Detroit, and another $4\frac{1}{2}$ per cent west of a line joining Sacramento and Portland, and the conditions will be better realized.

Our universities, geological surveys, and learned societies are relatively impecunious and cannot afford to subscribe to the whole range of published geological literature and are too widely scattered to facilitate pooling of resources in this direction. The result is partial starvation for literature. The position is steadily deteriorating as the exigencies of foreign exchange necessitate curtailment of even the existing subscriptions.

We are not sufficiently strong numerically or financially to produce even one specialist geological periodical. Some of our surveys, but not all, publish their results fairly frequently, and most of our scientific societies issue regular proceedings covering all branches of science. Our universities cannot publish independently. We have, therefore, very inadequate material to offer on a barter basis. Altruistic generosity on the part of our American friends helps us greatly and is deeply appreciated by institutions and individuals alike. We desire to reciprocate to the best of our ability, recognizing the intrinsic inequality of the exchange. Extension of the exchanges would assist us greatly.

Those more fortunately situated than we are could assist us

greatly, and themselves not a little, if it were possible to issue more numerous and complete annotated bibliographies at frequent intervals. An attempt was made in one of the Australian scientific societies a number of years ago to secure mutual assistance in keeping abreast of the flood of new literature, particularly that in foreign languages read by only a comparatively few of the members, by means of periodical meetings for the pooling of information. The numbers of members proved too few and their ordinary preoccupations too exacting for the method to be a success. It is essentially full-time work, if reading and annotating are to be maintained adequately and systematically.

With the much larger numbers of trained workers available, the much greater linguistic range provided by the widely derived population, and the more copious funds at their disposal, would it not be possible for some of the American learned institutions to prepare such bibliographies? By arranging that certain institutions should take particular sections, neither the volume nor the cost of the work would be prohibitive. The American workers themselves would benefit, and we onlookers believe that their breadth of outlook, considerable though it is, would be materially widened. Works like the *Annotated Bibliography of Economic Geology* have paved the way; but the field is extensive and cannot be covered by any single publication. Even we "little people" would be encouraged to increase our efforts if we could feel that we were part of a big organization and were not simply "taking in one another's washing."

Failing the compilation of special bibliographies, could not the numerous American geological periodicals arrange among themselves to cover, without duplication, the fields of foreign literature and spare a few pages in each issue for annotated bibliographies?

STUDIES FOR STUDENTS

A NEW PROJECTION PROTRACTOR. II*

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ANGLE PROBLEM

Required to find the (initial) bearing of Boulder Dam (v) from Teruel (t) of Figure 5 (p. 306), given these two points plotted in the stereographic and gnomonic projections of Figure 10 (p. 316) by methods already outlined. Since $T''O$ ster. (or TO gnom.) represents north from Teruel, it is required to measure $<OT''V''$ (stereographic) or $<OTV$ (gnomonic).

The stereographic solution is to find the pole of OT'' at y and of $T''V''$ at W and measure arc Wy with the net of the projection protractor holding its axis along yO, its equator on Oa'. Or since T'' is the angle-point of arc Wy, lines $T''W$ and $T''y$ cutting the primitive at i and y establish this angle as arc iy or $<iOy = 48°$. An alternative solution is to remember that T'' is the pole of arc $yWam$, and thus arc am measures the required angle, just as an arc measuring angular distance along the equator of the earth (regarded as a sphere) subtends an equal angle at the pole. This arc may be measured with the net of the projection protractor held as described above; or by using angle-point T'', it is found to be equal to arc $a'm' = <a'Om'$. The answer is then N. 48° W. To fly from Teruel to Boulder Dam by the shortest route, one would thus start with this course but would gradually bear more to the west, heading due west at W' (56° N. Lat., 54° W. Long.—some 250 miles northeast of Cape Harrison, Labrador), and finally traveling S. 44° W. ($<OV''T''$) as Boulder Dam came into view. By centering the net of the projection protractor to pivot around a needle at O, the bearing at the point along $V''T''$ cut by the equator of the net (extended below the base of the semi-net to the $r = 2$ cm. gnomonic scale) can be read very rapidly by counting the small circles along the great

* Continued from p. 323.

circle of the net lying above W from the nearest pole of the net to W. The azimuth of this bearing point is easily read from the primitive where cut by the zero-point of the upper scale.

For the various gnomonic solutions drop lines perpendicular to OT (the diameter of the primitive through the vertex of the required angle) from the points conjugate to T, the vertex of the required angle. Thus drop a normal from T'' (the stereographic face-pole of t, Fig. 5), locating h on the zone-line VT; from a (where Oa in stereographic degrees = $90 - OT$ in gnomonic degrees), locating b on VT; and from e' (where Oe' in gnomonic degrees = $90 - OT$ in gnomonic degrees), locating b' on VT. A radius through h establishes j on the primitive. The required angle is then $< TOj$ = arc $wj = 48°$. However, if ab is read along the upper scale of the projection protractor with its zero-point (O of Fig. 2, p. 296) at a, a more accurate figure for the desired angle is obtained with much less effort. An explanation of these methods is given ahead under "Measuring Angles in the Gnomonogram." The solution analogous to the last one given under the stereographic method is to measure great circle $e'b'$ of which T is the pole. This = $< e'T''b'$ = arc $a'm'$ (since Om' is parallel to $T''b'$). Note that b', which is 90° from T, could have been established by a normal to WT through W or by a normal to PT through O (where P is the pole of $b'T$). The bearing at any intermediate point between T and V is easily obtained. Thus, what is the course when crossing the meridian of 95° W. Long. (at 48° N. Lat., near Red Lake, Minnesota)? Draw this meridian; erect a normal to it where it cuts arc $V''T''$ locating a point on VT through which draw a radius and read the angle along the primitive between this and the given meridian, in this case 57°, or a bearing of S. 57° W.

The applications of the angle problem to the geological sciences are tied in with general projection solutions; some of these are elucidated under rotation problems ahead.

MORE DIFFICULT EXAMPLES OF DISTANCE AND ANGLE PROBLEMS

New wrinkles appear in projection solutions if we assume a problem involving both northern and southern hemispheres.[27] What does

[27] Actually, such a problem is more easily handled on a meridian projection than on the equator one used throughout this paper. See S. L. Penfield, *Amer. Jour. Sci.*, Vol. XI (1901), pp. 123–24, and Vol. XIII (1902), pp. 259–60.

"hemisphere defense" mean in terms of distances to be covered? Let us be conservative, leaving out Hawaii, and take the triangle embraced by three points: ***A*** (in the Yukon northeast of Juneau, Alaska) of 60°19′ N. Lat. and 132°37′ W. Long.; ***F*** (near the east tip of Tierra del Fuego) of 55°18′ S. Lat. and 65°18′ W. Long.; and ***G*** (near the south tip of Greenland) of 60°19′ N. Lat. and 47°23′ W. Long. If the co-ordinates of these three points are given their φ and ρ values, we then have

	φ	ρ
A	132°37′	29°41′
F	65 18	145 18
G	47 23	29 41

For point F, $180° - \rho = 34°42'$.

Plot gnomonic face-poles A, F, and G in the projection of Figure 12 by the methods already outlined; also plot f antipodal to F. Draw the great circle Af and erect a normal to it through O (giving the line of measures ZW) and a line parallel to it through O (locating C and D at the primitive). With center Z and radius $ZC = ZD$ locate W; or W may be plotted with the projection protractor, since OW measured in stereographic degrees = the complement of OZ in gnomonic degrees. Find the center P of arc $CA'f'D$ along OW beyond W (use the projection protractor as in Fig. 4, *b*, remembering that OP in gnomonic degrees = 90 − OZ in gnomonic degrees; or plot by making $ZCP = ZDP = 90°$) and draw this arc; an equal distance out from O along OZ find the center P' (beyond the margin of Fig. 12) for dashed arc CF' and draw it. These arcs serve to locate stereographic face-poles A', f', and F'. Similarly, P'' is the center for arc $A'G'$; note that A is the pole of PP''. Place the axis of the net of the projection protractor on CD and read $A'f'$ by counting small circles along the 18° great circle.[28]

A more accurate result may be obtained by locating m and n on the primitive by a straight edge on W through A' and f' or by run-

[28] This problem could have been solved much more rapidly had A' and f' been plotted directly with the projection protractor and then the net of the latter pivoted on O until a great circle cut these two points; i.e., it is not necessary to draw any arcs to solve the problem.

ning lines out from O parallel WA and Wf (using both methods serves as a check). The distance A to f (A' to f') thus = arc mn ($= <mOn = <AWf$) $= 52\frac{1}{2}°$; but f is antipodal to F; thus the distance A to F (A' to F') $= 180 - 52\frac{1}{2}° = 127\frac{1}{2}°$, which is equivalent to 8,798 miles, assuming a sphere where $1° = 69$ miles.

In terms of the stereographic projection it should be easy to visualize great circle travel going from A' to C (where the equator is crossed at $95\frac{1}{2}°$ Long., west of the Galapagos Islands) to F'. Or, if

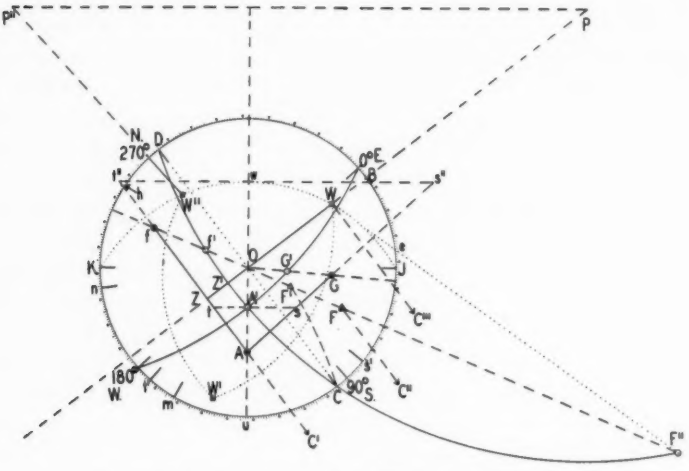

FIG. 12.—Gnomonostereogram of distance and angle problem

preferred, arc $f'A'$ may be continued to where it cuts OF extended, locating stereographic pole F'' (shown in a tiny circle; corresponds to pole F' shown in a tiny triangle); WF'' establishes e on the primitive, and arc $me = 127\frac{1}{2}°$. In the gnomonic it is equivalent to going from A out in the direction AC' (parallel to OC) to infinity and then back in the direction $C''F$ (parallel to CO) to point F.

In similar fashion the distances F to G ($116\frac{1}{2}° = 8{,}039$ miles) and G to A ($39\frac{1}{2}° = 2{,}726$ miles) may be computed, using W' and W'' Note that W' and W'' are easily located by arcs through W with centers at f and A. G is the center for arc $W'W''$. In short, $\triangle WW'W''$ is polar to $\triangle f'G'A'$. Thus $<f'A'G' +$ arc $WW'' = 180°$, and the same holds true for the remaining pairs of angles and opposite sides.

In flying the great circle route A to F (A' to F') what is the distance from A (A') to the equator at C' (C)? The answer is given by reading along the arc $A'C$ on the net of the projection protractor (with its axis along CD) or along the arc mC ($= <mOC$) of the primitive circle. The gnomonic solution is to read $<AWC'''$. This is 67° = 4,623 miles. The bearing at the equator is $<A'CO$ = S. 19° E. ($= WB = Z'O$; easily read with the upper scale of the projection protractor). The gnomonic solution is less easily visualized. Here AC' is the course, and OC is true south. These two lines are parallel in Figure 12. To find the angle between two such lines draw OZ normal to them through O; erect a perpendicular to OZ at O locating C (the angle point for the normal) on the primitive. Then $<ZCO = 19^\circ$ = arc hD (note that Oh is parallel to CZ and that h is on CZ' extended) is the required answer. This can be measured most quickly as OZ along the upper scale of the projection protractor held as in Figure 4, *b*. Had the angle been wanted between ZC' and some line parallel it not through O, which line cut ZO at X (not shown in Fig. 12), it would have been $<ZCX$, which could be measured as ZX on the upper scale of the projection protractor, as long as its zero-point (O of Fig. 2) had coincided with O of Figure 12.

Suppose one of our future bombers were ordered to fly this triangular route nonstop, going from F to A to G to F. It would come in to A (not allowing for drift) heading in the direction $C'A$ (bearing N. 41° W. $= <OAZ$ = arc $t'u$) and leave A in the direction AG. It would thus bank an angle $C'AG$ over A. This = $87\frac{1}{2}^\circ$, as is found by the following construction. Draw a diameter of the primitive through A, the vertex of the required angle. On this locate A' such that OA' in stereographic degrees equals OA in gnomonic degrees, and w such that Ow in stereographic degrees = $90^\circ - OA$ in gnomonic degrees. Then w is on arc JWK (JK is normal to AO) with center at A, since A is on the line of centers for point w. Drop normals to this diameter at A' and w, locating points t, s and t'', s'' on the sides of the required angle. Radii through t and s establish t' and s' on the primitive. Thus $<fAG = t's' = 92\frac{1}{2}^\circ$, and $<C'AG$ is the supplement of this. A quicker and more accurate type of solution is obtained by placing the top scale of the projection protractor along $t''s''$ with its zero-point at w; then read that $t''w = 41^\circ$ ($= t'u$) and $ws'' = 51\frac{1}{2}^\circ$ ($= us'$), whence $t''s'' = 92\frac{1}{2}^\circ$ ($= t's'$).

The same problem in stereographic solution means determining $<CA'G'$. To do this, draw arc KwJ of which the vertex A' is the pole. Then with the axis of the net of the projection protractor along KJ, read the distance along that great circle of the instrument which lies above KwJ between the points where this circle is cut by the sides of $<f'A'G'$. Or project these points to the primitive from A' and read the arc thus obtained. Of course, arc KwJ may be continued to where it cuts arc $A'CF''$, and the point of intersection joined with A' to locate a point on the primitive. Or find the poles of arcs $A'f'$ (at W) and $A'G'$ (at W''). Now place the axis of the net of the projection protractor along KJ and read the distance WW'' by counting along that great circle of the instrument which lies above WW''; or the arc along the primitive circle may be read between where it is cut by $A'W$ and $A'W''$. These last three methods give $87\frac{1}{2}°$, the supplement of $<f'A'G'$. When an angle is near 90° and one is not certain from inspection whether it is less or greater than a right angle, draw tangents at the apex of the angle to the two arcs and use an ordinary protractor (of course the tangents are normals to the radii of the arcs). If one considers $<f'A'G'$ to consist of $<f'A'O$ plus $<OA'G'$ and solves for each of these by the stereographic method, there is no confusion. Thus the pole of great circle OA' is taken as at J when measuring the first angle (arc JW) and at K for the second one (arc KW'').

MEASURING ANGLES IN THE GNOMONOGRAM

As previously stated, the only true angles of the gnomonic projection are, in general, those whose apices lie at the center of the gnomonogram, though the apex may lie on a radius if a right angle is involved (e.g., $<OZT$ of Fig. 10). For instance, $<OTZ$ of Figure 10 measures about 36° with an ordinary protractor; but, as already pointed out, it really represents an angle of 48°. For an explanation of the methods used in measuring angles on the gnomonogram, a new problem is introduced.

Given the euthygraphic projection of two great circles, VE and HE meeting at E, Figure 13; required to find $<VEH$. Draw EO (the radius through the vertex) and locate along it the three other points Z, Z', and W conjugate with E by means of the projection

protractor used as shown in Figure 11. Erect normals to EO at these points, thus locating M, M', and M'' along VE and N, N', and N'' along HE. Draw OM'' and ON'' establishing m and n on the primitive. Locate C' on OE so that $Z'C'$ = the radius of the primitive. The required angle is then equal to $\angle MWN = \angle M'C'N'$ = arc $mn = 180° - \angle DWF$, where D and F are the poles of HE and VE. The demonstration of the truth of this statement may proceed as follows: Since W is the angle-point for line DF whose pole is E, then the angular distance between M and N along the great circle MN equals $\angle MWN$. But M and N are on VE and HE, 90° from E; therefore this angle represents the true angle VEH, just as an arc measuring a certain angular distance along the equator of the earth subtends the same angle at either pole. Similarly, since D and F are 90° from N and M, respectively, $\angle DWF$ is the supplementary angle. The proof that arc $mn = \angle M'C'N'$ = the required angle is given in the following paragraphs; but note that, since this is true, $\angle M'C'N'$ can be measured with the upper scale of the projection protractor held along $M'N'$ with its zero-point at Z'. Under these conditions $Z'M' = 34°$ (= arc um) and $Z'N' = 33°$ (= arc un) where

	E	H	V
φ.....	47° 23′	00° 00′	90° 00′
ρ.....	59 41	30 04	32 11

A vertical section through ZE of Figure 13 is shown in Figure 14. Here triangles COE and ZOC are similar, thus $ZO \cdot CE = CO \cdot ZC$. But $ZC = ZW$; hence (1) $ZO \cdot CE = CO \cdot ZW$. In right $\triangle COE$, CW bisects $\angle OCE$; hence (2) $OW \cdot CE = CO \cdot WE$. (2) ÷ (1) gives $OW/ZO = WE/ZW$ or $ZW/ZO = WE/OW$, which may be expanded to $(ZW + WE)/(ZO + OW) = [ZE/ZW] = WE/OW$ or (3) $ZW \cdot WE = ZE \cdot OW$. But from Figure 13 tan $\angle ZEN = ZN/ZE = WN''/WE$, or (4) $ZN \cdot WE = ZE \cdot WN''$. (4) ÷ (3) yields $ZN/ZW = WN''/OW$. But since tan $\angle NWZ = ZN/ZW$ and tan $\angle N''OW = WN''/OW$, it follows that these angles are equal. In similar fashion one may prove $\angle MWZ = \angle M''OW$. Thus $\angle M''ON''$ = arc $mn = \angle MWN$. As an aside here, it may be

well to note from Figure 14 that $OE \cdot ZO = r^2$, since $OC = r$ and triangles COE and ZOC are similar. Moreover, $ZE \cdot ZO = \overline{ZW}^2$, since $ZW = ZC$ and since triangles ZCE and ZOC are similar.

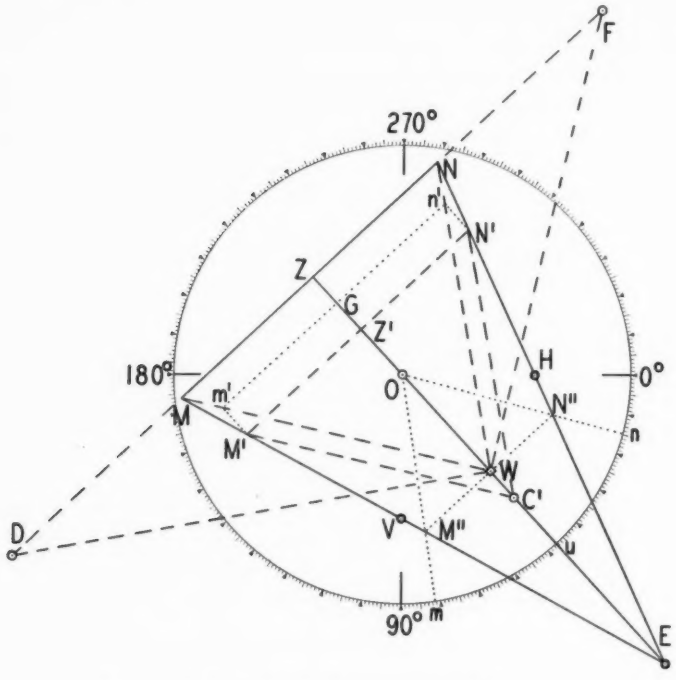

FIG. 13.—Angle problem in the gnomonic projection

It is easier to visualize the proof that $<M'C'N'$ also serves to measure $<VEH$, Figure 13. M' and N' lie along ME and NE where crossed by the normal to ZE through Z'. Draw $M'C'$ and $N'C'$ parallel to MW and NW, locating C'. Then by construction $<M'C'N' = <MWN$. Now consider the dihedral angle between planes MCE and NCE meeting in edge CE, where C is the center of the fundamental sphere. If this is rotated about MN as an axis through the

angle ρ for E, the edge CE will become vertical[29] (perpendicular to the plane of the gnomonogram) C going to W and E to a point orthogonally above W. The trace of the dihedral angle in the plane of the

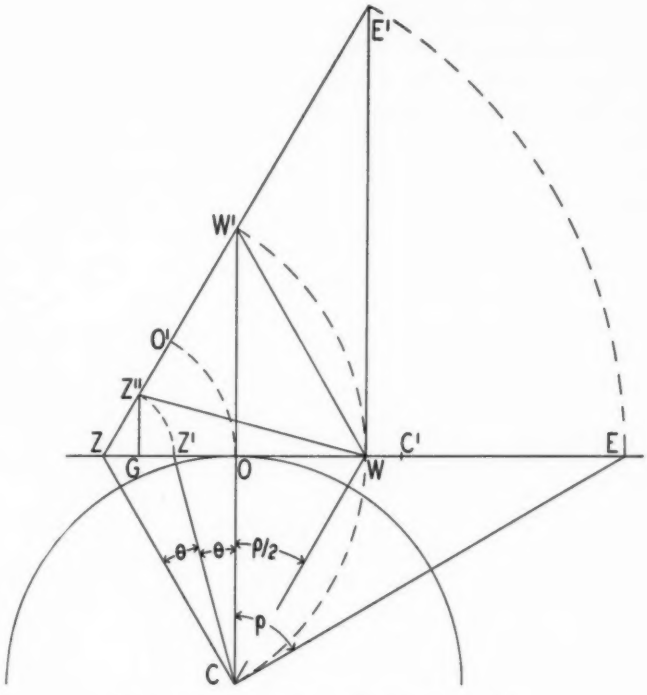

FIG. 14.—Vertical cross section along ZE of Fig. 13

gnomonogram then becomes MWN, and this plane angle is thus the measure of the true dihedral angle. In short, the euthygraphic pro-

[29] This is like rotating C and E (Fig. 14) anticlockwise about Z through the ρ-angle of point E, so that C goes to W, E to E'. Or visualize this as $\triangle ZCE$ rotating around Z to the position of $\triangle ZWE'$. It is then clear that E' is a point orthogonally above W of Fig. 13. Similarly, one can picture this rotation as carrying $\triangle ZCW$ (Fig. 14) into $\triangle ZWW'$. Since these are two equal isosceles triangles, W' must be a point orthogonally above O. In analogous fashion Z' rotates to Z'' and projects orthographically to G.

jection MEN represents the trace of a dihedral angle in the plane of the gnomonogram. On rotating this angle about MN, the gnomonic projection of the edge CE (of which point E is the euthygraphic projection), until this edge is vertical, point E moves to W and the angle now appears as MWN. During this rotation line $M'Z'N'$ lying in triangle MEN moves to a position orthographically[30] above line $m'G\,n'$ of triangle MWN. But GW is equal to the radius r of the fundamental sphere.[31] Hence, by the principle of construction of the projection protractor $<m'Wn'$ can be measured with the upper scale of the instrument along $m'n'$ with its zero-point at G. But $M'N'$ is parallel and equal to $m'n'$, and $Z'C' = r$;[32] hence $M'N'$ may be used in lieu of $m'n'$, since by construction $<M'C'N' = <MWN$, the required angle.

ROTATION PROBLEM

Rotation of a face-pole about an axis is, in effect, movement of the face-pole about a small circle whose plane is normal to the axis direction; in short, the axis cuts the sphere at the poles of the small circle in question. Three cases arise: (1) the axis is normal to the primitive circle; (2) the axis is parallel the primitive; (3) the axis is neither normal nor parallel to the primitive.

Where the **rotation axis is normal to the primitive,** and thus its projection lies at the center of either the stereogram or gnomonogram, one simply describes a small circle centered at the axis and going through the face-pole in question and rotates the face-pole through the required angle measured with an ordinary protractor. Rotation of a line (great circle) about such an axis is easily handled by rotating any two nonantipodal points lying on the line and then passing a great circle through the two rotated points.

Where the **rotation axis is parallel the primitive,** the meridian stereographic net of the projection protractor leads to a quick solution, since it carries the vertical (90° inclination) small circles. This

[30] Note that point M' lies on ME by construction; thus point m' must lie on MW, and $m'M'$ must be parallel and = to GZ'. It thus follows that $WC' = m'M' = GZ'$.

[31] In Fig. 14 $\triangle$s $ZZ'C$ and $ZZ''W$ are equal (picture the former as rotated to the latter about Z); hence $Z''W = Z'C$ and $<Z''WG = \theta$. It follows that $\triangle$s $GZ''W$ and $Z'OC$ are equal; therefore $GW = OC = r$.

[32] Since $GW = r$ and $GZ' = WC'$, it follows that $Z'C' = r$.

may be illustrated by the geologic problem of two tilts.[33] Given an outcrop showing two sets of dipping beds (faults, joints, veins, etc). separated by an angular unconformity. Let us take the case where the beds above the unconformity (*U* of Fig. 15, where $\varphi = 270°$ corresponds to north) dip 30° to S. 25° E. and those below it (*L*) dip 56° to S. $12\frac{1}{2}°$ W. What were the direction and amount of dip of the lower beds before the second tilt; that is, when the upper beds were horizontal (assuming they were deposited in this attitude)?

Since *OU* is the direction of dip of the upper beds, it is clear that the normal-line *T'T* (strike of the upper beds) represents the axis of the second tilt. In short, if *U* is moved about this axis through 30°, it will go to the center *O*, and thus represent horizontal beds. But *L* must then move through the same angle about the same axis. Place the paper of Figure 15 above the projection protractor[34] so that *T'T* coincides with the polar axis of the net and *OU* with its equator. Note that *L* lies above the 60° small circle of the net. Follow along this circle toward the net's axis for 30° (counting by the great circles as they are crossed every 2°) and locate point *L'*. Draw *OL'* and note this has a bearing of S. 35° W. and a ρ angle (read along the upper scale of the projection protractor) of $35\frac{1}{2}°$. Thus, before the second tilt we may assume that the lower beds of our outcrop were dipping $35\frac{1}{2}°$ to the S. 35° W.

[33] Described in detail by the writer in *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXII (1938), pp. 1261–71; also see *ibid.*, Vol. XXIII (1939), pp. 683–85. The solution of the two-tilt problem is analogous to that used in the correction of local dips to allow for a regional tilt, or of cross-bedding dips to allow for true bedding (see P. Reiche, *Jour. Geol.*, Vol. XLVI [1938], p. 907).

[34] Either use tracing paper or else work on a glass-topped table lighted from below. The protractor may be fastened down with two strips of Scotch cellulose tape, first running a thumbtack through it, so that the pointed end sticks up at *C* of Fig. 2. The thumbtack should be shortened and sharpened with a file, so as not to make too large a hole in the protractor. If the paper is weak, stick a tiny piece of gummed paper or cloth tape on it to take the needle hole. For class use the writer has drilled a fine hole in a piece of window glass and in this is mounted a sharpened thumbtack with celluloid-in-acetone cement. The glass is ground out so that the base of the thumbtack is flush with its lower surface. The protractor is laid on this with the thumbtack going through it at the center of the net; it is kept from rotating by two strips of 0".025 thick plastic cemented to the glass plate along the sides of the protractor. This apparatus is conveniently used over an ordinary glass-topped drafting table lighted from below; equally suitable is one of the small lighted glass-topped boxes available from dealers in stencil supplies.

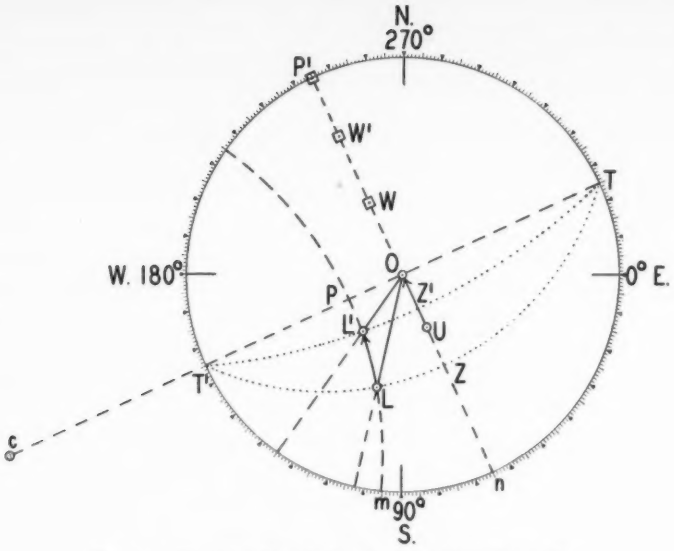

FIG. 15.—Stereographic solution of the problem of two tilts

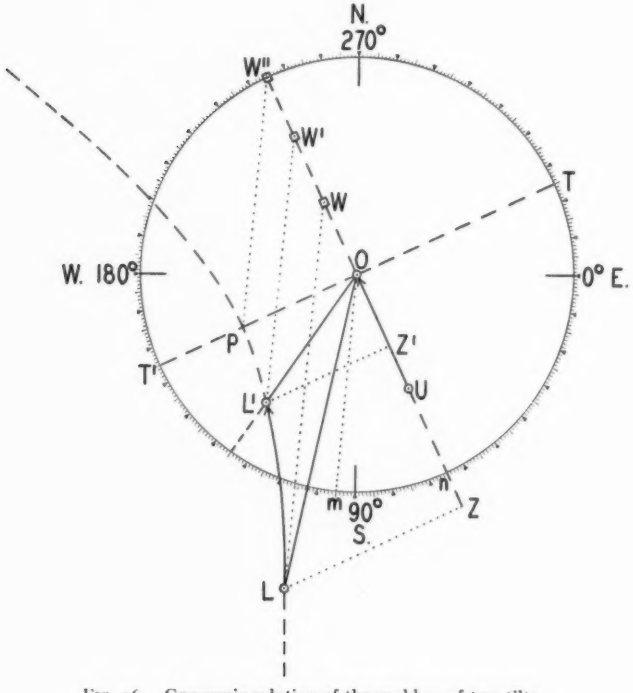

FIG. 16.—Gnomonic solution of the problem of two tilts

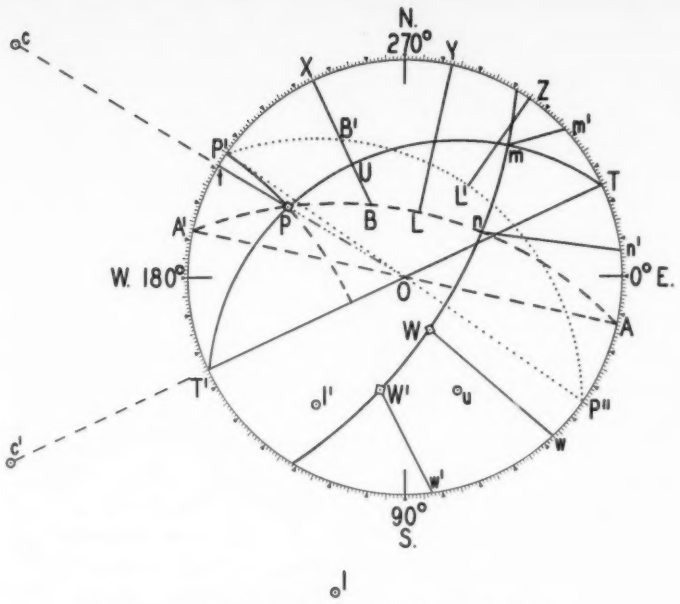

FIG. 17.—Cyclographic solution of the problem of two tilts

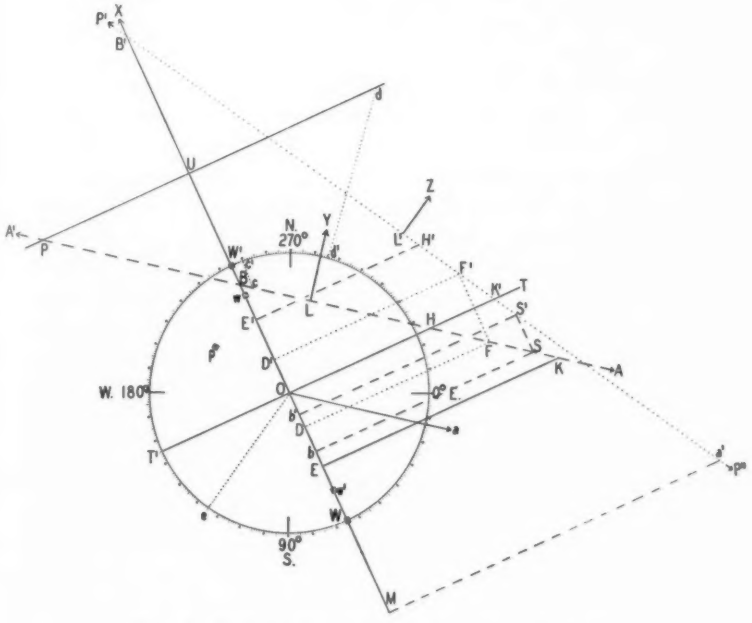

FIG. 18.—Euthygraphic solution of the problem of two tilts

The same problem worked on the gnomonic projection is given in Figure 16 where U, L, $T'T$, and OU have the same significance as they do in Figure 15. Draw LZ parallel to $T'T$, and with the upper scale of the projection protractor read that $OZ = 49°35'$. Locate Z' in 30° from Z (thus $OZ' = 19°35'$) and draw $L'Z'$ parallel to $T'T$. Locate the angle points W and W' for LZ and $L'Z'$, respectively. Thus OW = 90 − 49°35′ = 40°25′ ster. and $OW' = 90 - 19°35' - 70°25'$ ster. Through W' draw a line parallel WL locating point L', whose polar co-ordinates $35\frac{1}{2}°$ to the S. 35° W. yield the desired answer.

The rotation of point L is along a circle in Figure 15 (whose center c is easily found by the method of Fig. 3,*a*), but along a hyperbola asymptotic to Om in Figure 16, where point P is located on $T'T$ by a line through W'' parallel to WL, since W'' is the angle-point for $T'T$. The lines LZ, $L'Z'$, and PO of Figure 16 represent great-circle arcs 30° long (= arc mn, where Om is parallel to WL) normal to both OU and the hyperbola $PL'L$. Similar great-circle arcs are shown with dotted lines in Figure 15, in which W, W', and P' are the poles of great circles LZ, $L'Z'$, and PO, respectively. Straight lines WL, $W'L'$, and $P'P$ all meet the primitive at m and $\angle LZ = \angle L'Z' = \angle PO$ = arc mn.

The rotation of a line about an axis may be handled in terms of the rotation of any two nonantipodal points lying on the line. Thus let Figure 17 represent the cyclographic solution of the same problem as solved stereographically in Figure 15. Then continuous-line arc $T'UT$ represents the tilted upper beds of dip XU (XU = dip-direction, $\angle XT'U$ = dip-angle). Dashed-line arc $A'LA$ of dip YL shows the present tilted lower beds. To level up the upper beds continuous-line arc $T'UT$ must flap down to the primitive along $T'XT$. Point P at the intersection of the two arcs must go to P'. P' lies on the primitive where cut by WP extended, if W is the angle-point (pole) of $T'UT$. If one wishes to draw vertical small-circle arc PP′, note that P' is 60° along the primitive from T'; thus use the method of Figure 3, *a* to find its center c' on OT' extended. The diameter of the primitive through P' gives the strike of the lower beds before the second tilt. Now locate B' out 30° from B along the normal to the axis of the second tilt. To do this, use the upper scale of the projec-

tion protractor with its zero-point at O. Place the axis of the net of the projection protractor along $P'P''$ with its equator on OZ (normal to $P'P''$) and observe that B' lies just outside the 54° great circle (cf. Fig. 2). Lay off $OL' = 54\frac{1}{2}°$ with the upper scale of the projection protractor and, using the instrument as in Figure 4,*b*, find the center l' for the dotted-line arc of great circle $P'L'P''$. Note that the centers u, l, and l' for drawing the three arcs of Figure 17 are identical with face-poles U, L, and L' of Figure 16. ZL' of Figure 17 thus represents the dip of the lower beds before the second tilt.

This problem can also be solved without drawing arc $P'L'P''$, since the strike of the lower beds before the second tilt is given by the diameter through P' and the dip is the same as $<TPA$, the angle between the upper and lower-bedding planes. Strike the great circle whose pole is P with center c, locating m and n on PT and PA, respectively. This great circle goes through W, since W is the pole of $T'UT$; it also goes through W', the pole of $A'LA$. A line through Pm locates m' on the primitive; one through Pn fixes n'; and arc $m'n'$ is thus the angle of dip of the lower beds before the second tilt. Or one can get this angle by measuring the angle between W and W', the poles of the arcs making up the sides of the angle. Draw PW and PW' extended locating w and w' on the primitive and the arc ww' is the required angle. Note that the straight line OP (shown by dots and dashes) is the direction of contact of the bedding planes of the lower and upper strata after the second tilt; the horizontal trend of this contact line is S. $58\frac{1}{2}°$ E. (given by tO), and it dips $25\frac{1}{2}°$ ($= tP$) in this direction. $P'O$ is the direction of this line of contact before the second tilt. Problems dealing with the directions of intersections of a vein and a fault plane, or of outcrop lines of faults on quarry or mine walls, may be solved in this manner.

Rotation of a line in the gnomonic projection may be illustrated by handling the same problem euthygraphically. This is shown in Figure 18. The corresponding points of Figures 17 and 18 have the same letters. Thus PU represents the present upper beds where $OU = 60°$ gnom., and so XU represents their dip (remember X designated by an arrow corresponds to a point out infinite distance in the direction of the arrow). Similarly $A'A$ stands for the present lower beds of dip YL, and thus $A'A$ is to be rotated 30° about $T'T$

in the direction OU. $A'A$ cuts OU at B, and $OB = 40°20'$ (measured with the upper scale of the projection protractor). Locate B' on the diameter normal to the axis of the second tilt such that $OB' = 30° + 40°20' = 70°20'$. B' is thus a point on the required line, since points in a plane normal to an axis of rotation remain in that plane throughout the rotation. While the projection protractor is still in place, locate b and b', the angle points for lines parallel the rotation axis through B and B', respectively. Note that $bb' = 15° = \frac{1}{2}$ the second tilt angle. Draw bS and $b'S'$ parallel the rotation axis; the former locates S on $A'A$. Make SS' normal the rotation axis, establishing S', a second point on the rotated line. Then $bS = b'S'$ (measured with the upper scale of the projection protractor with its zero-point at b or b') corresponds to the true angle made by the planes whose euthygraphic projections are $A'A$ and $P'P''$ with $B'O$. Thus line $A'A$ on rotating 30° about $T'T$ goes into line $B'S'$ or $P'P''$ part of whose central is ZL'. Hence the dip of the lower beds $P'P''$ before the second tilt is ZL', or $35\frac{1}{2}°$ to S. 35° W.[35]

Another method for finding a rotated special point is to remember that all great circles containing the axis of rotation remain perpendicular to the normal to the rotation axis during the rotation. Thus the great circle OH moves to the position $E'H'$ (where $OE' = 30°$ measured with the upper scale of the projection protractor), since both great circles include the rotation axis (which is parallel $T'T$ but goes through the center of the sphere, below O of Fig. 18, at C of Figs. 8 and 9). Find the angle points for $E'H'$ and OH at E and W, respectively, and draw EH' parallel to WH locating H' on $E'H'$.[36]

If inconvenient to use B, H, or K for finding the rotations to B', H', and K' of Figure 18, use any random point along $A'A$ and apply

[35] Of course, this problem can also be solved without drawing $P'P''$ in a manner analogous to the solution given in the preceding paragraph. Thus a normal to PD (where D is the angle-point of PU) through O locates e on the primitive, and Oe is the direction of dip of the lower beds before the second tilt. The amount of dip is $< UPA$, which is measured by arc $c'd'$ on the primitive (Op in stereographic degrees equals OP in gnomonic degrees and p lies on OP; a normal to OP through p locates c and d on $A'A$ and PU, respectively; Oc and Od determine the location of c' and d').

[36] An analogous method is to make use of the great circle EK (where $OE = 30°$), which on rotation moves to the position OK'. Since E' is the angle-point for EK and W' is that for OK', locate K' by making $W'K'$ parallel to $E'K$.

the method of Figure 16. Or locate M on the normal to the rotation axis such that $OM = 60°$ ($= 90° -$ the angle of rotation). Make Ma' parallel the rotation axis and through D', the angle point of Ma', draw a line parallel $A'A$ locating a', which is also on the rotated line $P'P''$. This procedure is made clear if it is remembered that before rotation the equator (which has O as its pole) is cut by $A'A$ at a point a, where Oa is parallel to $A'A$. After rotation this old equator moves to Ma' (the old pole moves to E') and old point a moves to new point a', where $< MOa = < MD'a' = < MBA$.

A seventh alternative method to locate a rotated special point is to lay off $OD = OD' = 15°$ or half the angle of rotation and draw DF and $D'F'$ parallel the axis $T'T$ locating F on $A'A$. Then through F draw a line normal to $T'T$ establishing F', which is on both $D'F'$ and the required new line $P'P''$. The explanation of this method may be thought of in terms of rotating the pole of the plane of projection from O to E'. Since by construction $OE = OE' = 30°$, we may visualize that as E goes to where O was, O goes to where E' was. Now a plane tangent to the sphere where it is cut by the line CE (where C is the center of the sphere and so directly below O of Fig. 18) intersects the gnomonogram in the line DF, and one tangent to the sphere where cut by the line CE' intersects the gnomonogram in the line $D'F'$. In short, before rotation DF marks the intersection of the plane of the gnomonogram with the plane that coincides with the plane of the gnomonogram after rotation, and $D'F'$ marks the intersection of these same two planes after rotation. Thus DF and $D'F'$ are the only lines common to the gnomonogram both before and after rotation; so in general they are the only lines along which no distortion or change of scale is involved on rotation. They are thus known as "isometric" or "common" lines, and any given linear distance measured out from the line of measures WW' along these two lines represents the same angular value. Thus $< DwF = < D'w'F'$, where w and w' are the angle-points of DF and $D'F'$, respectively.

This general problem of rotating points and lines about an axis parallel to the plane of the primitive is a common one, since it is often necessary to rotate the plane of projection so that some special point lies at the center of the new projection.

Where the **rotation axis is neither normal nor parallel to the primitive,** it is necessary to draw a small circle whose geometric and stereographic centers do not coincide and which has an inclination be-

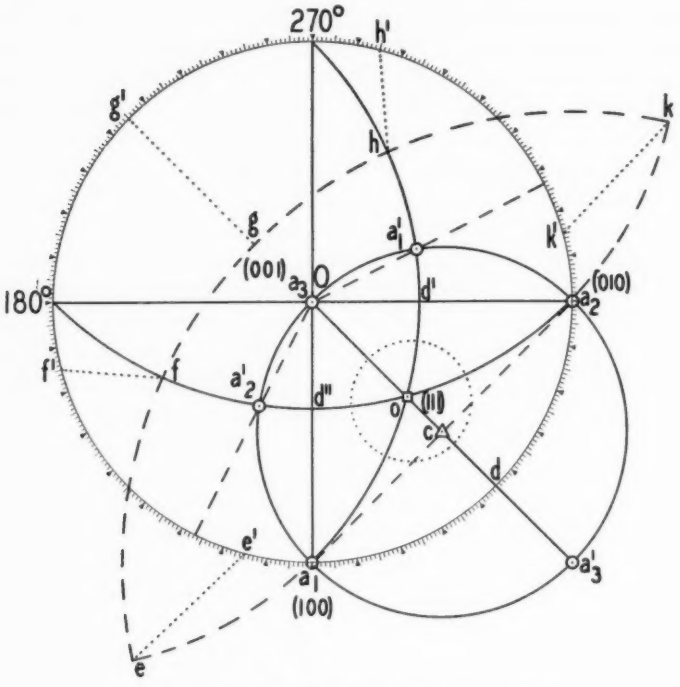

FIG. 19.—Stereographic solution of hemitrope problem

tween 0° and 90°. As an illustrative example[37] we may use a crystallographic problem. Given that [111] is the twin axis for a hemitrope; where do the hexahedron {100} face-poles of the twinned individual lie? In Figure 19 three of the normal individual hexahedron face-poles about this axis are shown in stereographic projection at a_1, a_2, and a_3, together with the cyclographic projection of the twin

[37] For an illustrative example in the field of geology see the writer's "Drillhole Problems in the Stereographic Projection," *Econ. Geol.*, Vol. XXXVI (1941), in press.

axis at o. The latter has $\varphi = 45°00'$ and $\rho = 54°44'$; thus Oo represents $54°44'$ (upper scale of projection protractor), and $Od' = Od'' = 45°$.[38] Locate a_3' on Oo extended so that $Oa_3' = 2(Oo) = 109°28'$

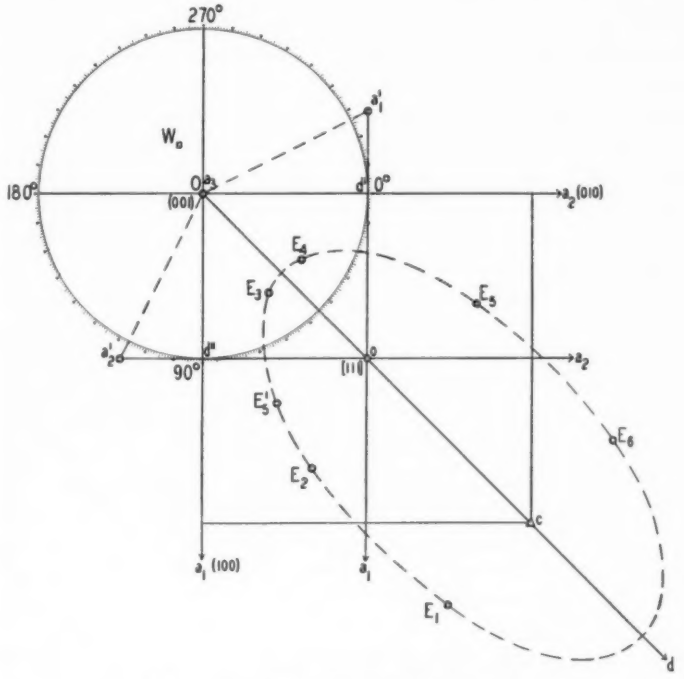

FIG. 20.—Gnomonic solution of hemitrope problem

[38] This problem where only a 180° rotation is involved can be solved more speedily by having the paper above the projection protractor with the center of the primitive at the center of the net (through which sticks a sharpened thumbtack), as is described earlier for a rotation axis in the plane of the primitive. Rotate the paper until any single great circle of the net lies below the twin axis and the face-pole to be rotated. Count the small circles along this great circle to get the distance between the two points in degrees. Lay off this same value from the twin axis along the same great circle but going away from the original face-pole to establish the corresponding face-pole of the twin individual. An alternative method is to find the pole of the great circle just mentioned and to pass a great circle through this pole and the twin axis. Then count along a small circle, normal to this last great circle, which runs through the face-pole.

ster. Oa_3' is the line of measures for our small circle. Now use the centimeter scale to find c ($Oc = ca_3'$), the geometric center of the small circle of inclination Oo whose stereographic center is at o, and strike the circle running through a_1, a_3, a_2, and a_3'. The point c lies at what would be face-pole (112) in the gnomonic projection. Since the six lines radiating out from o make 60° angles with each other,[39] it is clear that the hemitrope axis sends face-pole a_1 to a_1', a_2 to a_2', and a_3 to a_3'. Also, note that face-pole a_3' (in a tiny circle) represents the same face as does face-pole c (in a tiny triangle), since $cd = da_3' = 19°28'$, and continuous-line small-circle arc $a_1a_3'a_2$ represents the same small-circle arc as does dashed arc a_1ca_2. This latter arc is a straight line; this peculiar condition occurs when the plane of the small circle includes that pole of the primitive which is the center of projection.

Figure 20 illustrates this problem in the gnomonic projection, and corresponding points in the two diagrams are indicated by the same symbols. Note that a_1' and a_2' are plotted in Figure 20 from the polar co-ordinates of these face-poles read from Figure 19. It is easily seen from Figure 20 that these face-poles lie at points that in terms of the normal individual would have Miller indices $(\bar{1}22)$ and $(2\bar{1}2)$, respectively. The six lines radiating out from o make angles of 60° with each other, though these *seem* to be 45° and 90°. Face-pole a_3' (in a tiny circle of Fig. 19) can be represented in Figure 20 only by a face-pole in a tiny triangle at c. Thus in Figure 20, Oo is 54°44′, and o to c (in a tiny triangle) means going from o to d and back in (along the under half of the sphere) from d to c, which is also 54°44′, as is oa_1, oa_2', oa_1', and oa_2. The Miller indices of a face-pole at c (in a tiny triangle) would be $(22\bar{1})$ in terms of the normal individual.

Knowing the symbols of any one face a_1', a_2', or a_3' ($= c$), the other two could be found, since they would be a different combination of the same three digits. Were o to mark the point of emergence of a threefold symmetry axis and Od that of a plane of symmetry, the locations of all six face-poles demanded by this symmetry combination, given any single (hkl) crystal-face symbol, could quickly be

[39] To see this, draw the great circle fgh with center at a_3' of which o is the pole (and angle-point). This great circle is cut by the six lines radiating from o at e, f, g, h, k, and at oa_3' extended. Straight lines from o to these intersection points cut the primitive at e', $'$, g', h', k', and d, points 60° apart.

found. Thus plot $E_1(532)$ by Goldschmidt methods; the other five face-poles derived from this symmetry in clockwise order about o would be $E_2(523)$, $E_3(325)$, $E_4(235)$, $E_5(253)$, and $E_6(352)$. These all lie on an ellipse of eccentricity 0.868, which represents the cross section in the plane of the gnomonogram of an oblique cone of axis Co with half apical angle of $20°31'$. The cross section of this same cone in the stereographic is shown by the small dotted circle about o of Figure 19; this circle has a polar distance of $20°31'$. The corresponding conic section in the plane of the gnomonogram of Figure 20, which is the locus of face-poles about o at an angle of $54°44'$, is a hyperbola going through a_1, a_2', a_3, a_1', and a_2. Each of the six E face-poles lies in one of the "sextants" of the lower right quadrant made by the six lines radiating out from o. Where b = big, i = intermediate, s = small, any face-pole in each of these sextants will have Miller indices whose digits are in the ratio *bis*, *bsi*, *isb*, *sib*, *sbi*, and *ibs* (followed around in the same order as given above for the E faces). If lines are drawn from o to E_1, E_2, etc., these will each be $20°31'$ in length. Lines from the E face-poles with just the odd or just the even subscripts drawn to o will make 120° angles with each other, but the angle between any two adjacent such lines will be 38° or 82° (e.g., $< E_3oE_4 = 38°$, while $< E_4o\ E_5 = 82°$). Had one of the face-poles chosen lain on a line normal to Od through o, then each such line would have made 60° angles with its neighbors; this is the case with {423}, {534}, {513}, etc. Of course, the same is true if the face-pole lies on any one of the six lines radiating from o.

Given a [111] hemitrope (isometric); required to find where face-pole E_5 of the normal individual goes on the twinned individual. Draw the line E_5o and extend it to E_5', making the angle between E_5 and o the same as that between o and E_5'; this is determined by measuring from the angle point W. Note that E_5' has irrational indices in terms of the normal individual but is (253) of the twinned individual. This gnomonic procedure becomes a rather tedious task if done for many faces; the stereographic solution is generally time-saving. H. Hilton[40] has given a gnomonic solution for the problem of rotation of a random face-pole about a random twofold axis (as well

[40] "The Construction of Crystallographic Projections," *Min. Mag.*, Vol. XIV (1905), pp. 101–2.

as for rotation through any angle); those who have much such work which they prefer to do on the gnomonic projection should consult the original article.

REFLECTION TWIN

Reflection problems may be split into three categories, depending on whether the plane is parallel or normal to the primitive, or random. The solution of the first is obvious, and that of the second involves a simplification of the third, the only one here treated in detail. The problem of a z (232) reflection twin of staurolite is most easily done by means of the combined projections, using the stereographic to find the polar co-ordinates of the reflected face-poles, the gnomonic to check the accuracy of the stereographic and to prepare a perspective drawing. In the gnomonostereogram of Figure 21 the face-pole (232) is indicated by z' (stereographic) and z (gnomonic), and the plane itself by $C'Z'$ (cyclographic) and cZ (euthygraphic).[41] Required to find the positions of the face-poles on the twinned individual corresponding to m ($\bar{1}\,\bar{1}0$) and r ($\bar{1}01$) of the normal individual. Plot m', m, r', and r in Figure 21 and pass great circles through $m'z'$ and $r'z'$ and find their angle-points at W' and W, respectively. The centers for these great circles are at c' and c, respectively, since the line of centers for z' is Zc, for m' is Oc', and for r' is Dc. These great circles are normal to $C'Z'$ at K' and K, respectively, since they go through its pole z'. W' and W are also the angle-points for the euthygraphic projections of these great circles, which are mz (parallel to mO) and rz.

Lines from W' through m' and K' establish points m' and x on the primitive; the same points may be checked by radii parallel to $W'm$ and $W'L'$. Lay off an arc $xy = m'x$ establishing y on the primitive. $W'y$ then fixes $\bar{m}'$ on the great circle $m'z'$ so that $m'K' = K'\bar{m}'$. Similarly, a line parallel Oy through W' establishes $\bar{m}$ on mz. Note that $\bar{m}'$ and $\bar{m}$ should lie on the same radius and $O\bar{m}'$ (stereographic) should $= O\bar{m}$ (gnomonic).

[41] The axial ratio is taken as 0.47 : 1 : 0.68, though this c value is double that for the unit cell. Under these conditions the polar co-ordinates are:

	φ	ρ	$90-\rho$
r (101)	90° 0′	55° 16′	34° 44′
p (111)	64 40	57 55	32 5
z (232)	54 37	60 31	29 29

In like manner Wr' or a radius parallel to Wr locates a on the primitive, and WK or a radius parallel WL establishes b. Lay off arc $bC'' = ab$, and then line WC'' fixes $\bar{r}'$ on $r'z'$ while a line parallel OC'' through W locates $\bar{r}$ on rz. Then $\bar{r}'$ and $\bar{r}$ should lie on the same radius, and $O\bar{r}'$ (stereographic) should $= O\bar{r}$ (gnomonic).

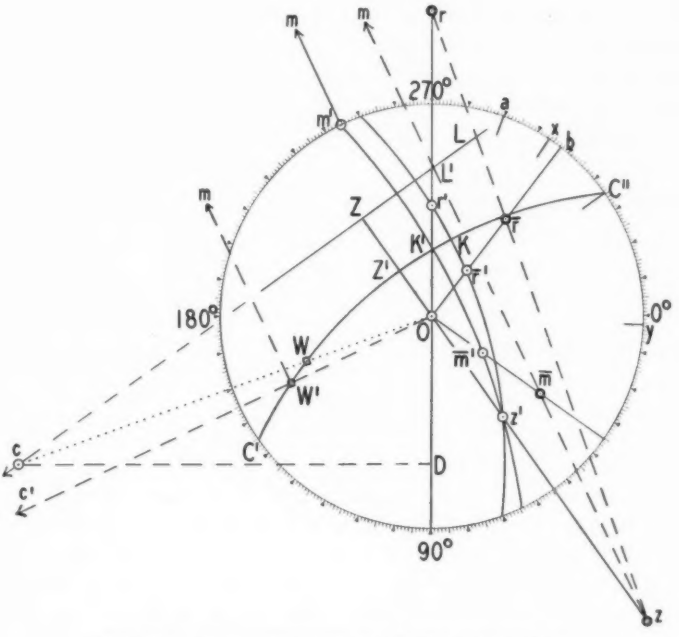

FIG. 21.—Gnomonostereogram of reflection twin problem

It is time-saving but less accurate to use the net of the projection protractor to solve this problem. After plotting z, z', Z', m', and r', draw arc $C'Z'C''$ with center at z. Place the paper above the protractor on a glass-topped table lighted from below (or use tracing paper) and, with a needle through O of Figure 21 and C (Fig. 2) of the protractor (or a sharpened thumbtack sticking up through the center of the net, as described earlier for a rotation axis in the plane of the primitive), rotate the paper until some single great circle of the net lies below z' and the face-pole concerned (here m' or r').

Count the degrees along this great circle from this face-pole to arc $C'Z'C''$ and continue an equal number of degrees establishing the corresponding face-pole of the twinned individual. An alternative method with the same points plotted is to rotate the paper till great circle $C'Z'C''$ lies above a great circle of the net and then follow along a small circle from the face-pole concerned across $C'Z'C''$ an equal angular distance to find the new face-pole.

Had a face-pole such as (110) more than 90° from arc $C'Z'C''$ been chosen for this problem, the procedure would have been as described, except that the other half of the great circle would have been used (designated by a dashed-line arc through C' and C'' with the same curvature as $C'Z'C''$ but on the other side of O, and representing a great circle on the lower hemisphere), and the twinned individual face-pole would lie on the lower hemisphere.

CRYSTAL DRAWING

Those interested in preparing crystal drawings in standard position from gnomonograms will find it convenient to use the guide-line shown just below the left side of the net of the projection protractor (Fig. 1). Lay a straightedge along this line and the $74\frac{3}{4}°$ mark on the right edge of the projection protractor and with a mounted needle scratch lines on the top of the protractor near its right edge and the left corner of the base. With a straightedge along these lines, use a right-angle triangle to find where a normal to this guide-line through the center of the $r = 5$ cm. net (C of Fig 2) cuts the inside edge of the 80° great circle of this net; here punch a needle hole marking the angle-point W. With this guide-line "horizontal" (parallel the top and base of the sheet of paper) and the angle-point below it (e.g., protractor rotated some 160° anticlockwise from its normal position), CS of Figure 2 corresponds to the $+b$-axis, CO to the $+a$-axis, of the rectangular crystal systems.

In similar fashion a parallel guide-line is located for the $r = 2$ cm. net by joining the 74° point on the base of the projection protractor with the 88° point on the right edge of the instrument; as before, the angle-point lies on the normal to this direction through the center of the $r = 2$ cm. net where this normal cuts the 80° great circle of the small net.

REVIEWS

Strength and Structure of the Earth. By REGINALD ALDWORTH DALY. New York: Prentice-Hall, Inc., 1940. Pp. ix+434; figs. 85. $3.50.

Strength and Structure of the Earth is primarily a study of isostasy. Probably the greatest service rendered in Professor Daly's new book is his bringing together and making readily available the widely scattered data which are necessary for a critical consideration of this troublesome subject. The need for such an assemblage and scholarly presentation of the pertinent facts has been felt by many geologists who wish to appraise the available geodetic evidence and form their own opinions of the role of isostasy in earth behavior. Much of this material has now been brought together and integrated by one of the most widely read of geologists. The approach is principally geodetic and geophysical, acquainting the reader with the successive steps by which the investigations have advanced.

The volume begins with an excellent account of the development of the idea of isostasy. Testing isostasy with the plumb line is the next major topic. A companion chapter on the measurement of gravity and comparison of intensities naturally follows. In this the different methods of reducing the gravity readings to the geoid are clearly described and briefly discussed. The succeeding 178 pages comprise five closely related chapters of notable value: "Gravimetric Tests of Isostasy in the United States by Hayford and Bowie"; "Later Gravimetric Tests of Isostasy in North America"; "Testing Isostasy in Europe"; "Testing Isostasy in Africa and Asia"; and "Testing Isostasy at Sea." Here one finds the chief results, factual and interpretive, obtained thus far in the different regions of the globe where gravity determinations have been made. Particularly useful are the many comparisons of the free-air, Bouguer, Hayford, and Airy anomalies. The differences between these must, in their very nature, be of help in disclosing the causes and significance of the isostatic anomalies in the various regions and thus facilitate solution of the general problem of earth deformation.

Of more than average interest and value are the results obtained in India and the discoveries by Vening Meinesz in the East Indies. The several hypotheses of compensation do not fit the facts so well in India as in some other regions. In peninsular India the anomalies reveal a hidden

range flanked by two broad belts of large gravity deficiency which are interpreted as troughs. Glennie's hypothesis of crustal warping deduced from these has been well considered by Daly and an attempt made to bring it into accordance with his views.

Meinesz' development of a good method for measuring gravity at sea was a great step forward. His finding of the very striking narrow strip of negative anomalies paralleling the coasts of Sumatra and Java and bending around a part of the Banda Sea, and the fitting of this into the isostatic and geologic pictures of the region have done much in the last few years to bring isostatic data and orogenic processes and concepts into satisfactory harmony. Daly's treatment of these investigations is appreciative and clear-cut, although he is not in complete agreement with some of the deduced theoretical conclusions.

"Nature's Experiments with Ice Caps" (assuming that Nature be still experimenting in deformation of the lithosphere) is the title of a chapter on one of the author's favorite topics. His interpretation of these "experiments" is that isostatic adjustment following addition of mass by glaciation, or removal of mass by deglaciation, has probably been accomplished by flow in a relatively thin asthenosphere immediately below the lithosphere. If this is so, he thinks the strength of this postulated asthenospheric layer must be extremely small. The argument that the absence of a belt of pronounced upbulge of the earth's surface peripheral to the areas of glaciation is contrary to expectation on the hypothesis of isostatic outward flow beneath the ice caps, Daly believes, is met by showing that the flow would be concentrated at great depth and that the expected peripheral bulge should be much wider and much lower than has been pictured by most other investigators.

The thoroughgoing analysis of isostatic evidence and deductions leads to the final climacteric chapter, "Strength of the Earth Shells." Daly concludes that the strength of the lithosphere in continental areas is perhaps twice that of granite in a testing machine and is still greater under the deep oceans; that the asthenosphere is vitreous and devoid of strength, or nearly so; and that beneath this is a solid, crystalline mesosphere of greater density and considerable strength extending to the inner core. The essentially strengthless asthenosphere thus permits ready isostatic adjustments to fit the requirements of the ice-cap experiments and the geodetic conclusions that, in many regions, the earth's "crust" is not far from a state of isostatic equilibrium. Embarrassment, however, is caused by the seemingly large departures from equilibrium in peninsular India, Turkestan, and some of the ocean deeps. Heiskanen's 1938 formula of a

triaxial earth spheroid (with the long axis of its equatorial ellipse emerging at 25° west longitude and 155° east longitude), if used for reference in place of a rotation spheroid, appears to reduce the discrepancies. The author gives much attention to the reduction in anomalies resulting if the true figure of the geoid be such a triaxial spheroid. Still this apparently helps only in part.

The triaxial shape, if a verity, would require considerable strength in the earth to maintain its deviation from a spheroid of rotation. This being too much to expect of the lithosphere as defined, Daly has been led to seek the requisite strength in a thick mesospheric shell beneath the asthenosphere. This he thinks is solid and crystalline due to pressure. Some geologists have held the opinion that the temperatures at the depth of the asthenosphere may be too high to permit the crystalline state and that a glassy state would therefore prevail there. If such be the case, one may well wonder why a mesosphere, still deeper and presumably somewhat hotter, should not likewise be glassy. Or perhaps one should discard this opinion and attribute the postulated weakness of the asthenosphere to conditions close to the melting point, heat overcoming the effect of pressure in that zone, but not sufficing to do so at greater depth.

According to the present study the postulated triaxial figure of the geoid is the weak surface manifestation of a more declared triaxiality in the strong mesosphere, where this shape is maintained by the strength of the material. Assuming the density of the top of the mesosphere to be greater than that of the asthenosphere immediately above, an equipotential surface of the asthenosphere, behaving as a liquid, should have a curvature bearing resemblance to that of the upper surface of the mesophere, and this triaxial shape is thought to have some expression in the geoidal surface as well. Utilizing the principle still further, Daly assumes that the surface of the mesospheric shell is humped beneath the large areas of positive anomaly and hollowed beneath those of negative anomaly. Under these conditions much of the stress indicated by geoidal departures from the figure of a perfect rotation spheroid would be borne by the mesospheric shell, and to that extent the great loads indicated by the large areas of one-sign anomaly would not be a tax on the strength of the lithosphere. Decreasing the supposed load stresses in the lithosphere in this way is Daly's method of bringing the apparent great departures from isostatic equilibrium into harmony with the isostatic theory. That this is the explanation of the rather abrupt change from the strong positive anomalies of the Tonga Plateau to the strong negative anomalies of the Tonga deep, however, may be doubted.

A satisfactory explanation for deep-focus earthquakes originating in a zone of practically no strength is not easy to find. Daly, however, has pictured various possibilities, commanding admiration for his ingenuity and exceptional fertility of ideas. Very candidly he emphasizes the highly speculative nature of these suggestions. Yet without such expression of new and daring ideas, progress will be slower than with them, for they focus attention and stimulate thought.

The two best features of this new book are its admirable survey of isostatic investigations, which is of great value to any student of the subject, and the very clear presentation of the author's own deductions and constructive thinking based upon these. Some of the theories advanced are distinctly individualistic and may not meet ready acceptance. The real test will be how they work out in the future; in the end, one good step forward should justly outweigh several false steps in such elusive and difficult problems. In spite of the complexity of the subject matter, this book is easily read.

R. T. C.

Geology of the Chicago Region. By J HARLEN BRETZ. (Illinois State Geological Survey Bull. 65, Part I.) Springfield, Ill., 1939. Pp. 118; pls. 7; figs. 91.

In a little over a hundred pages Mr. Bretz has provided the inhabitant of the Chicago region with a stimulating summary of the geology of his domain. Things are quite adequately explained and undue technicalities avoided. The Chicagoan will find here, fitted into a logical sequence of origin, just about all the ups and downs and peculiarities of his terra firma which he may encounter on various trips about the city's outskirts. Much, too, that he would not be likely to observe is called to his attention for its value in interpreting the landscape of Chicagoland, or for its curiosity value and lack of satisfactory explanation, as the case may be.

The booklet has many excellent illustrations from both photographer and draftsman and carries a map (2 miles to the inch) of the surface deposits over an area 53 miles long (north and south) and 25 miles wide. Many pages are devoted to elementary treatment of such things as weathering, soils, stream erosion, wave activity, and land surveys about Chicago, all of which are especially adapted for the resident unfamiliar with geology.

Of considerable interest are discussions of the Silurian reefs (metropolitan ones, with suburbs!), Mississippian fossils in fissures of the Niagaran limestone, historic records of the progress of valley and shore

erosion, the great depletion of artesian water, and the troubled course of Calumet River. Other interesting items include the amount of spit-fingering along the shores of Lake Chicago, the contrasting relationship of the earlier and later shorelines of this lake to its valleys of westward outlet, and the pre-Toleston valley buried in shore deposits.

By way of criticism the reviewer notes particularly the lack of agreement with recent discoveries concerning the pre-Nipissing stages of the Great Lakes; for instance, where Mr. Bretz states "the Nipissing beach in Georgian Bay is at least 40 feet below the lowest of the Algonquin beaches," it should be realized that the Nipissing beach actually transects these earlier beaches in Georgian Bay, so as to lie below them in the north but above them in the south. To be initiated the account recalls a certain failure in dovetailing of the stages of Lake Chicago with lake stages in the Huron basin which must have corresponded. Although this may be due partly to a divergence in nomenclature, the present integration of later events in the two basins leaves something to be hoped for. This imputes nothing to Mr. Bretz, but simply states a gap which may be filled presently. Perhaps the Huron basin will reveal evidences of the pre-Calumet and pre-Toleston low-water stages which are inferred in the Chicago region. Perhaps in the latter area the true Algonquin (3-outlet?) beach will be discriminated from or identified with the Toleston beach.

The effect of the opening paragraphs is good. Mention should be made of the author's imagination which quickly transports the reader into the spirit of the subject. It reaches considerable height in the metaphoric battle and final rout of the ice sheet. But the reader by then must have become accustomed to height. Strange it may seem that to learn about the earth on which he stands, our Chicagoan at the outset is whisked away from it as rapidly as possible to the top of the Tribune Tower for a bird's-eye view! Perhaps Mr. Bretz forgot that he left the reader there. The enthusiasm which is evident in the author's style does much to enhance the publication, and the Chicagoan who avails himself of it will appreciate this as well as the clear presentation.

GEORGE M. STANLEY

Studies of Cenozoic Vertebrates and Stratigraphy of Western North America. By PAUL C. HENSHAW *et al.* (Pub. 514.) Washington: Carnegie Institution of Washington, 1940. Pp. 194; pls. 24; figs. 20. $2.75.

This publication is made up of nine papers by various authors, all of which deal with mammalian fossils of California and Oregon.

C. W. STERNBERG

Petrology and Genesis of the Third Bradford Sand. By PAUL D. KRYNINE. (Pennsylvania State College, Mineral Industries Experiment Station, Bull. 29.) State College, Pa., 1940. Pp. vi+134; figs. 37.

This report is based on a detailed quantitative study of six drill cores from the Bradford field and less detailed study of other cores from this and near-by fields. Three hundred and fifty thin sections and 600 heavy mineral residues from the Bradford area were examined. In addition 200 thin sections and 225 mineral residues were examined from other Paleozoic formations.

No short abstract can do justice to the great quantity of factual detail included in this bulletin. The careful and astute observations recorded by Krynine on this sedimentary unit will be of value to students of sediments everywhere, as well as to those with more direct interest in the sedimentary history of the Appalachian geosyncline. About 25 pages are devoted to the mineralogy and about the same number are given to the petrography (thin-section studies and size analyses) of the Bradford sand. The 14 pages on the texture and pore pattern will be of special interest to petroleum engineers and geologists interested in water-flooding and other recovery problems. Some 11 pages deal with the petrology and origin of the Third Bradford Sand. Appendixes, mainly tables of data, form the balance of this work.

The Third Bradford Sand—essentially a graywacke—is derived mainly from older Paleozoic sands and old metamorphics, though no less than nine major stratigraphic units made contributions. Deposition in quiet brackish water after a tumultous but brief transport following extremely violent erosion is recorded by the Bradford graywacke cycle. The evidence leading to this conclusion is skilfully assembled and fully presented by Krynine.

F. J. PETTIJOHN

Resource-Full Kansas. By KENNETH K. LANDES and OREN R. BINGHAM. Lawrence, Kansas: State Geological Survey, 1940. Pp. 64.

The annual value of mineral output in Kansas is over one hundred and fifty million dollars, a value exceeded by only six states. Simply written and illustrated with a great number of excellent pictures, this little booklet shows why the state is one of the leading producers of mineral wealth.

C. W. STERNBERG